Expanding the coverage of ecosystem services in life cycle assessment: an interdisciplinary venture

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Chapter 6

General Discussion

The aim of this thesis was to investigate whether and to what extent we can incorporate the assessment of ecosystem services in LCA studies. In particular, I investigated if existing ecosystem service methods could be compatible with the impact assessment phase of LCA, and to propose approaches for the development of characterization factors (CFs) that can aid on the implementation of new impact categories that are directly linked to ecosystem services. In this chapter I discuss the findings for each of the research questions addressed in this thesis, starting in section 6.1.1 with an overview of the ecosystem services already included in impact assessment methods and the identified gap towards a proposed optimal coverage (RQ1). Aiming for a way forward, I discuss in section 6.1.2 a new impact category proposed to assess one of the ecosystem services identified as missing, and the considerations taken to reconcile differences between existing ecosystem service methods, the impact assessment phase of LCA and available LCI data (RQ2). While our approach is applied to characterize the influence of land use impacts on pollinator abundance, the recommendations derived can be applied to other ecosystem services that present similar characteristics.

Two main challenges for the development and successful incorporation of ecosystem service assessment in LCA were addressed in this thesis. Firstly, the compatibility of the CFs with LCI data, which can facilitate or hinder their applicability (RQ3), and secondly, the representation of biogeographical and socioeconomic variation that is relevant for ecosystem services, within country-specific CFs (RQ4). Addressing the first, the advantages of expert elicitation methods to tackle key data gaps are discussed in section 6.1.3, along with valuable insights retrieved from the stablished interdisciplinary collaboration (**Chapter 4**). In section 6.1.4, the use of Land System Archetypes (LSAs) is discussed as a viable approach to incorporate both biogeographical and socioeconomic parameters during the development of characterization factors, illustrated with the case of land use impacts on soil erosion. Lastly, limitations on the current characterization of land use impacts are discussed in section 6.2.1, followed by reflections on the societal relevance of improving the assessment of ecosystem services and other key environmental impacts in LCA studies (section 6.2.2).

6.1 Bridging the gap

6.1.1 Ecosystem services in LCA: where are we now?

For the determination of the current state of ecosystem services in LCAs and to present an overview of the results achieved by previous studies, the first step of this thesis was to conduct a review and analysis of ecosystem services found within current impact categories. While some of the previous studies had focused on developing recommendations for future integration of ecosystem service assessment, none had presented an overview of those already covered and/or linked with commonly used impact assessment methods. To achieve this, we investigated the impact assessment family 'ReCiPe2016', and found that multiple ecosystem services can be considered to be directly and indirectly assessed through a handful of impact categories, providing further evidence that the assessment of ecosystem services is operationally compatible with current LCA practices. This is exemplified by the multiple midpoint impact categories assessing the availability and provision of resources such as water, minerals and fossil resources. In the case of water use, the effect of this impact on ecosystem services is assessed further to the Area of Protection 'Ecosystem quality', through endpoint damage pathways that estimates the potential reduction of net primary productivity and plant diversity.

The CICES categories of ecosystem services that were deemed as compatible for environmental LCA were summarized in Chapter 2. From this inventory, we found that approximately 4 overarching categories are completely missing from both LCAs and from the literature proposing concrete indicators for the inclusion of ecosystem services in LCA. Examples of such ecosystem services are the provision of genetic resources, as well as the regulation and maintenance of pest and disease control. Given the high diversity of ecosystem services, there are major challenges for the development of a generalized framework that can encompass all missing categories. However, a practical approach as recommended by this thesis, is to focus on key ecological features and processes that can be found close within the cause-effect impact pathway of an ecosystem service. This can facilitate the development of CFs for midpoint and/or endpoint indicators, allowing to incorporate new impact categories that can be directly linked to ecosystem services.

Focusing on the impact assessment phase and in particular on the development of characterization factors, aligns with efforts by previous studies (de Baan et al. 2013; Beck et al. 2010; Saad, Koellner, and Margni 2013) and those listed in Figure 6.1. An approximate amount of seven overarching ecosystem services categories have been addressed by previous studies proposing midpoint indicators. However, the proposed impact categories had not yet been included in families of impact assessment methods such as ReCiPe2016. Alternative approaches as the ones proposed by Blanco et al. (2017), who targeted the incorporation of ecosystem services through inventory flows, and Cao et al. (2015) who focused on the development of weighted endpoint indicators, exemplify the diversity of approaches that can be considered, providing promising opportunities to increase the number of ecosystem services that could be represented in LCA studies. However, a wide application of any of the proposed methods is dependent on the actual incorporation of the relevant inventory data and CFs into common LCI databases and families of impact methods. Without such links, newly proposed methods are usually limited in applicability. Therefore, it is recommended to increase efforts towards the integration of already proposed impact categories targeting ecosystem services, which would increase the coverage from an average of 4 to approximately 10 out of 15 ecosystem services categories proposed as optimal.

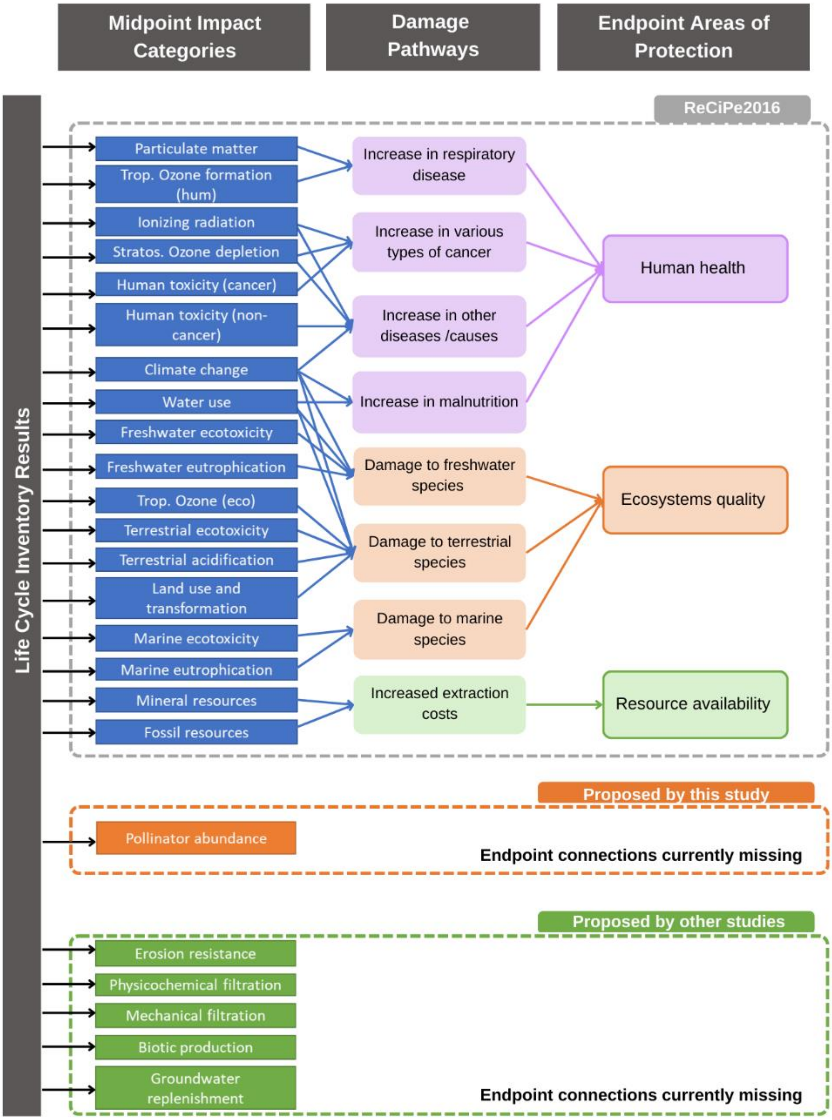

Figure 6.1 *Overview of impact categories from ReCiPe2016 and those proposed to include ecosystem services in LCA.*

6.1.2 Proposing a new impact category: Land use impacts on wild pollinator abundance

One of the ecosystem services identified as missing from LCA studies in **Chapter 2**, was the service of crop pollination. While one-third of the global food crops rely on pollination, steep insect declines have led to the estimate that crop production might fall by 5% in high-income countries and 8% in low-to-middle income countries in the absence of pollinators (Hallmann et al. 2017; Koh et al. 2016a; Potts et al. 2010). Even if these numbers are not yet considered dramatic in itself, they will increasingly become so in future since it is likely that our dependence on pollinators will grow over time as global diets diversify towards more nutrient-rich food, among these, fruits, vegetables and nuts (Aizen et al. 2019; Garibaldi et al. 2008). Furthermore, several low-income countries rely on the trade of pollinator dependent crops, such as cocoa, coffee, soybeans, palm oil and avocados, where a steep decline of pollinators would only increase their economic vulnerability. Due to their high relevance for ecosystems and human welfare, the development of a new impact category for LCA targeting the explicit assessment of land use impacts on wild insect pollinator communities was tackled in **Chapters 3** and **4**.

While searching for existent impact assessment models that could be used to characterize pollination impacts in LCA, we found, as anticipated, that the major limitation for a direct application was the lack of specific temporal and geographical data in LCA that was needed by most methods to determine the amount the pollination supply. Generally, information regarding the location of pollination dependent farms, type of crops grown and estimates of pollinator abundance, are needed by most methods to derive an index of pollinator supply and their contribution to crop pollination and crop yield. Such information is not available in LCAs, because LCA studies rely on inventories where the amount of environmental pressure associated with a product system, in this case the amount of land in use recorded and aggregated in terms of m^2 and $m^2 \cdot$year, are usually deprived of explicit spatial and temporal characteristics, such as georeferenced data or times for pesticide application rates.

To overcome these limitations, **Chapter 3** focused on the characterization of pollinator abundance, which is a representative measure on the state of pollinator communities, and it has been positively correlated with their capacity to provide crop pollination services (Genung et al. 2017). After establishing collaboration with an expert in the field of pollination, the information available in LCA inventories was used to derive wild pollinator abundance estimates based on expert knowledge, allowing to characterize the influence of different land use practices on pollinating insects. This approach can be replicated for similar ecosystem services (Figure 6.2), where an ecological feature or process that is directly correlated with the capacity to provide the service can be found within the cause-effect chain, increasing its compatibility for midpoint characterization. Consequently, the application of existing impact assessment models to produce characterization factors, or to derive one, will ultimately depend on the data requirements of the model and their availability in LCI databases. Such data gaps, both for the derivation of CFs and to improve LCA inventories, can be tackled in multiple ways, for example by primary data collection, literature reviews or expert elicitation methods, as illustrated in **Chapter 4**.

Figure 6.2 *Recommendations to approach the assessment of ecosystem services in LCA and examples from this thesis.*

6.1.3 Deriving readily applicable characterization factors and the importance of interdisciplinary research

To move from illustrative to readily applicable CFs, a bigger sample of pollinator abundance estimates was obtained. To do this, an invitation to collaborate was sent to nearly a hundred experts in the fields of pollination and wild pollinators. From those invited, 25 researchers confirmed participation for a Delphi expert elicitation assessment, and an active collaboration was established. Building up on the characterization approach proposed in Chapter 3, generic CFs were derived in Chapter 4, providing values that allow translation into relative pollinator abundance impacts for 24 land use categories. To retrieve the pollinator abundance estimates for each land use category, the Delphi expert elicitation assessment proved to be a useful method allowing to gather not only quantitative data, but also to obtain argumentation on the characteristics of the landscape associated with each estimate, and to highlight important sources of variation, such as biogeographical differences and management practices.

As a result from the extensive argumentation provided by experts during the Delphi assessment, extensive and intensive levels of agricultural practices were directly correlated with the degree of pollinator abundance impacts. The different degrees of abundance associated with the resulting CFs, were consistent with trends found in the literature, where both modelled and sampled data reflect intensive land use as highly correlated with steep decline rates of pollinator abundance (Bennett et al. 2014; Hallmann et al. 2017; Koh et al. 2016b). This decline has been reported to span several orders of magnitude, across multiple geographic locations and taxonomic groups (Bergholz et al. 2022; Ke et al. 2022; Millard et al. 2021). These findings highlight a key challenge for global food production. Achieving high crop yields can present benefits beyond food security and farmer incomes, as it can help reduce the amount of land needed for food production (Garibaldi et al. 2016; Kwapong et al. 2016; Stein et al. 2017). However, high crop yields are currently achieved in most countries by intense management practices involving a considerable amount of fertilizers and pesticides, which in return reduces ecosystem quality and increases dependency on agricultural inputs (Cole et al. 2020; Dhankher and Foyer 2018). The challenge is therefore to find ways in which crop yields can be increased without compromising ecosystem resilience, including pollinator abundances, for instance by a smart mix of both intensive and extensive practices.

Further modelling efforts are still needed to assess the validity and uncertainty of the CFs proposed, which should be thoroughly analyzed for their integration in decision making. A combination of uncertainty and (global) sensitivity analysis are recommended for future research to aid on the determination of highly influential parameters, their effect on land use, pollinator communities, and the potential tradeoffs when accounting for multiple impact categories. While combined methods of uncertainty and global sensitivity analysis are still not a standard practice in LCA studies, there is a growing body of work aimed at their development as a way to improve the interpretation capacity of life cycle impacts and the identification of highly influential parameters (Blanco et al. 2020; Cucurachi et al. 2022; Cucurachi, Borgonovo, and Heijungs 2016; Kim et al. 2022). Moreover, the variability associated with the (subjective) abundance estimates retrieved for each land use category can serve in future research as informative prior distributions which, once coupled with field data, could help improve the robustness of predictive models of pollinator abundance.

Considerations for the aforementioned parameters is needed to design agro-ecosystems that can manage agricultural inputs and limit the damage to insect populations while providing high food security. This potential tradeoff highlights the need for a better understanding of the benefits that can be achieved by restoration and maintenance practices that can help reestablish floral and nesting resources (Albrecht et al. 2020; Kaiser-Bunbury et al. 2017; Lettow et al. 2018). The benefits of, for example, hedgerows and flower rich field margins, are implicitly accounted for in the high abundance estimates retrieved during the Delphi assessment. However, explicit land use processes addressing these practices are not currently included in life cycle inventories, nor are processes containing information regarding managed pollinators. These are important activities that should be considered for incorporation in the inventory and impact assessment of LCA studies to help distinguish key differences between agricultural systems. From our results, the range between typical and high abundance estimates, as well as the CFs that are based on negative abundance values (reflecting a positive influence on abundance), could be used as the basis for future studies looking for a first approximation or illustrative ways on how to reflect these benefits in LCA.

6.1.4 Addressing regionalization and intranational variation in country-specific characterization factors

An important aspect to address when discussing the implementation of ecosystem services in LCA, is the regional variation of impacts, in particular when discussing land related stressors as the ones characterized in **Chapter 4**. Unlike impacts such as climate change, where an emission of 1kg of CO_2-eq on one side of the world will have the same effect as when it would be emitted on the opposite side, other type of impacts such as those related to land use, will tend to considerably differ based on biogeographical characteristics. To portray these differences, multiple studies have aimed for the development of regionalized CFs (Núñez et al. 2013; Saad et al. 2013) and regionalized impact assessment methods such as LC-Impact (Verones et al. 2016). However, the application of regionalized CFs is generally limited by their compatibility with the spatial scales available in commonly used LCI data (Koellner et al. 2013). Unit process data in LCA databases are usually presented as globally generic and/or country-specific values, as exemplified by the largest and most worldwide used database for LCA, ecoinvent. Therefore, considering countries as the highest level of specificity for most background processes, we explored in **Chapter 5** if the representation of key intranational variations could be better represented when producing country-specific CFs for the case study of soil erosion.

As common practice during the characterization of land use impacts, previous studies had produced country-specific CFs for soil erosion based solely on biogeographical parameters and using the Potential Natural Vegetation (PNV) as a reference state (Beck et al. 2011; Koellner et al. 2013; Saad et al. 2013). The PNV refers to the assumed state that the land would spontaneously develop towards to, if the absence of human action continues during a sufficient length of relaxation time (i.e., regeneration time). A few would argue that PNV represents a natural situation that in some cases cannot be assumed as representative: "If we assume for a moment that all human pressure were to be removed, it would take a long time for a potential natural forest to grow; indeed, it would take so long that the climate would probably change again in that time" (Loidi et al. 2010). Therefore, using the concept of PNV as reference state can complicate the interpretation of results and increase discrepancies on the analysis of land use related impacts. Furthermore, using the PNV as reference state does not allow to allocate or differentiate between the impacts that might have occurred a long time ago and the impact incurred on by the activities related to the functional unit, especially in the case of land transformation impacts. Two other alternative reference states are usually proposed in the literature, one refers to the use of a (quasi-)natural land cover present in each biome/ecoregion, and the other to the 'current mix' of land uses (Koellner et al. 2013; Koellner and Scholz 2008). By using the soil erosion rates associated with each LSA as a reference state in **Chapter 5**, the 'current mix' is used and prevailing soil erosion can be accounted for, ultimately reflecting a more realistic estimate on the potential soil erosion impact that is associated with the functional unit assessed. I argue that this is a more useful impact assessment than a comparison in reference to PNV. While the use of PNV as reference state can help maintain consistency during characterization, our results indicate that the risk of underestimating impacts can be substantial when prevailing degradation is not accounted for, especially for vulnerable areas that might be overlooked when only the most predominant biome or ecoregion per country is assumed as representative.

To elaborate further on the LSAs used in **Chapter 5,** these were produced by Václavík et al. (2013) with the use of self-organized maps (SOMs). SOMs refer to an unsupervised neural network that is trained (using unsupervised learning techniques) to reduce data dimensions and to build a discretized representation from the input samples (Kohonen 2013). In this case, the LSAs were derived from a large amount of data covering a wide range of indicators related to land use intensity, socio-economic and environmental factors. This allowed to identify representative patterns and key characteristics that could be used for the characterization of impacts. While the characterization of soil erosion impacts is usually based solely on biogeographical parameters (e.g., slope, average precipitation, etc.), the regions that were particularly vulnerable to further soil degradation were characterized by a high degree of agricultural inputs, low GDP and strong dependence on agricultural production. Thus, accounting for socio-economic factors can aid on the identification of geographical hotspots that might be overlooked when only ecological parameters are considered (Qin et al. 2021).

Given the large number of indicators that could be used for the derivation of archetypes with the use of SOMs, I recommend to explore the development of an archetype classification that could be used as input across several impact categories (Beckmann et al. 2022; Guinée, 1995). This could be derived from a meta-analysis focusing on data requirements across impact categories, to keep consistency and minimize the proliferation of category-specific archetypes. A combination with uncertainty and sensitivity analysis are further recommended to differentiate the varying effects of quantity and model uncertainties, as well as to allow for the identification of parameters that can drive the largest part of uncertainty associated with a model output (Cucurachi et al. 2022).

Parameters of land use intensity are a clear example of relevant data that can be used across several impact categories, such as type of croplands, fertilizer input, irrigation and yield rates. This data could be used in future research to regionalize the characterization factors presented in **Chapter 4** for pollinator abundance, and provide useful input for measures regarding soil quality and ecological resilience. Moreover, parameters such as species richness, which is used for the characterization of biodiversity impacts, and socio-economic factors such as population density and accessibility, are both useful during midpoint and endpoint characterization of human health related impacts.

Along with the aim to improve the assessment of ecosystem services in LCA, it is inevitable that the number of impact categories available will also expand, highlighting the need to focus integrative efforts on the harmonization of data that can lead to results at spatially relevant scales while facilitating decision making. According to the results obtained in **Chapter 5**, world generic CFs can underestimate over ten times the degree of impacts associated with land use types such as mining, landfill, fallow ground, and permanent crops. Based on these findings, I consider the refinement of country-specific CFs a worthy endeavor that can help improve the representativeness of land use impacts and ES assessment in LCA, without compromising the compatibility of the CFs with inventory scales, and allowing for an easier application and interpretation.

6.2 Limitations and outlook

6.2.1 The issue of land use and land transformation

The environmental impacts addressed in Chapters 3-5, were directly related to land stressors. As explained in Chapter 3, typically two type of land use impacts are assessed in LCA studies: 1) occupation impacts, assessed during the land use phase, and 2) transformation impacts, which considers the time required for an ecosystem to recover after land conversion and abandonment; permanent impacts are usually considered by assuming no regeneration possible and assigning the maximum degree of impact possible. While transformation impacts should provide information on the reversibility of an intervention (i.e., how fast an ecosystem recovers after land conversion), we observed two main discrepancies.

The first discrepancy was found while analyzing the inventory flows recorded for agricultural processes in the main LCA database ecoinvent. The elementary flows for land transformation are currently linked to unit processes by two types of entry: "land transformation from land use type *x*" and "land transformation to land type *y*", as two separate flows (Figure 6.2). The net sum of these two separate flows is then multiplied by their corresponding characterization factor to estimate the land conversion impact (Althaus et al. 2007). However, it was noticed that in multiple relevant agricultural unit processes, the same land use class for transformation "from" and "to" was used, with the same value for each flow (e.g., "transformation *from* 1m^2 of annual crops" and "transformation *to* 1m^2 of annual crops"), which implies no net transformation impacts. While the decision on how to allocate transformation impacts is complex and can vary depending on assumptions regarding production output times and reference states, the current approach creates difficulties for interpretation of the results, hindering a clear representation of the contribution of land conversion and occupation flows (Scherer et al. 2021).

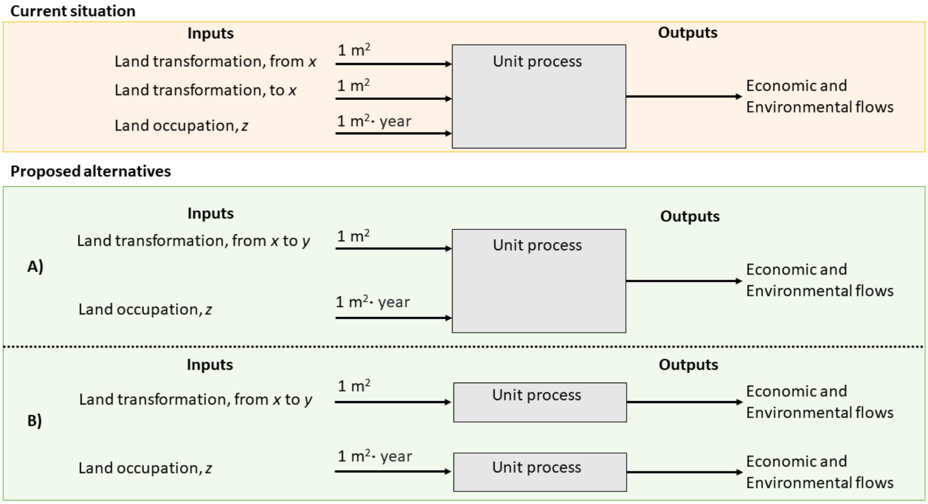

Figure 6.3 *Illustration of land flows connection and proposed alternatives.*

I recommend to address this in future research by exploring the creation of net impact inventories for land transformation flows (Figure 6.3), where a single elementary flow for land transformation (e.g., "land transformation from *x* to *y*') can be used as input for the relevant unit processes and multiplied by their corresponding characterization factor. This new net inventory flow could be included in the same way that both land occupation and transformation flows are used as input in unit processes that incur on land stress (Figure 6.3; alternative proposed A), or by separating the net land transformation flow as input for a land conversion specific unit process (Figure 6.3; alternative proposed B). The latter alternative would allow for additional considerations of land conversion to be modelled independently from land occupation, allowing for an easier analysis of flows contribution.

Furthermore, a detailed analysis proposing net transformation flows could focus on the identification of the most representative land classes to derive characterization factors. For example, the "transformation from *x* to *y*" could be characterized for a set group of the most relevant land use classes, such as forest, grassland, annual and permanent crops, among others. Further specificity could be achieved by targeting the identification of relevant land transformation impacts from land classes within the main categories (e.g., "transformation from annual crop *x* to annual crop *y*"). As discussed in section 6.1.4, special attention will have to be given to the selection of reference states, where the selection between potential natural vegetation or a previous natural state will result in different magnitudes and interpretation of the estimated impacts.

A second discrepancy found was during the characterization of land use impacts, and refers to the fact that multiple methods assume the same effect factor for occupation as for transformation impacts, with the latter multiplied additionally by the regeneration time. This leads to an impact assessment where habitat change is only considered more damaging if the ecosystem recovers slowly, and where the actual impact of land conversion might be misrepresented. Land conversion is one of the primary drivers linked to species decline, and its accurate assessment remains an essential step towards a comprehensive estimation of ecosystem impacts in LCA studies. As displayed by our results in **Chapters 3-4**, we did not produce CFs for land transformation as to not perpetuate practices that seem to undermine efforts towards a better impact characterization. This reinforces the previous recommendation of focusing efforts on an in-depth analysis of how land transformation impacts are currently assessed in LCA, both in terms of inventory data and the development of characterization factors, and propose harmonized ways to improve their assessment.

6.2.2 Societal relevance

The increased acceptance of the LCA framework has resulted in a considerable amount of knowledge produced across several sectors and governmental efforts attempting to quantify environmental pressures. While still acknowledging its limitations, it has led to the recognition of LCA as a representative and valuable method to estimate environmental impacts. A practical example of this is the case of the Netherlands, which is one of the first countries in Europe to legally require a standardized LCA report, in some cases known as Environmental Product Declarations (EPDs), in order to obtain certification for building products and building performance (National Milieu Database 2022; Sobota, Driessenn, and Holländer 2022). For this, companies and governmental organizations are relying on EPDs and LCA results to compare the environmental impacts associated with different material and building design alternatives.

EPDs, and in general LCA results, rely on the availability of impact assessment methods to portray a comprehensive array of environmental impacts, and key ecosystem services remain absent from such comparisons. This can lead to an oversight of impacts and potential benefits associated with sustainable practices. For example, in the case of biomaterials, their increased use is an integral step towards a sustainable built environment (Churkina et al. 2020; Göswein et al. 2021; Vázquez-Núñez et al. 2021). For this, sustainable sourcing of raw materials is indispensable to strive towards regenerative systems and avoid resource depletion. However, common impact assessment methods used in LCA are limited on their ability to reflect key differences between different forest management practices and their influence on the ecosystem services provided by forests, which include but are not limited to, food, fuel and fibers provision, filtration of air pollution and water supplies, control of floods, contribution to soil erosion resistance capacity, biodiversity and genetic resources (as well as cultural ecosystem services related to recreation, education, and cultural enrichment) (Hua et al. 2022; Kiran et al. 2023). Thus, the omission of a comprehensive ecosystem service assessment hinders an accurate representation of the benefits and potential impacts associated with different wood sources and their associated product systems, creating a blind spot during decision-making aimed at a sustainable built environment (Nocentini, Travaglini, and Muys 2022; Tiemann and Ring 2022).

This legal requirement in the building sector clearly illustrates the way in which LCA and other relevant methods are becoming part of governmental efforts aimed at a transition towards more sustainable systems, and highlights the need for a continuous improvement, both in terms of accuracy and coverage, of the impact assessment methods we rely on. To address important shortcomings such as this one, further research is recommended at the interface of LCA and disciplines dedicated at the assessment of environmental impacts, in order to expand and improve the impact assessment and interpretation of LCA results in a meaningful way. For this, extensive collaboration and interdisciplinary work is essential, both to improve the quality of LCI data and for the incorporation of field specific knowledge required in impact assessment models for characterization, as illustrated by this thesis in **Chapter 4**.

6.3 Conclusion

To contribute to the body of knowledge aiming at a better coverage of ecosystem service assessment in LCA studies, this thesis dived into the challenges of incorporating existing ecosystem service methods within the impact assessment phase of the conventional LCA framework. Through this thesis, we present an overview of ecosystem service categories that could represent an optimal coverage for their inclusion in LCA, and provide a clear example on how to overcome the challenges of characterizing key environmental impacts that are otherwise missing or misrepresented in LCA results and that influence the quality and supply of ecosystem services. We demonstrate the approach proposed with the development of readily applicable CFs that will allow future LCA studies to account for land use impacts on pollinator abundance, and provide further evidence on the benefits of interdisciplinary collaboration as a way to strengthen our capacity to estimate anthropogenic impacts, with the use of expert elicitation methods as a valuable tool to fill in key data gaps. Lastly, we recommend to continue efforts towards an overarching archetype classification that can facilitate the inclusion of multiple biogeographical and socio-economic factors for the identification of representative patterns, and provide input across multiple impact categories at relevant spatial scales.

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