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Chapter 7

Answers to the research questions

7.1 Answers to the research questions

As indicated in Chapter 1, the objectives of this thesis are to identify the key issues when conducting an LCA of residue-based bioenergy and to propose improvement in LCA procedures, specifically in the areas of LCI, LCIA, and methodological choices in the comparative LCA. It was discovered that the key issues associated with residue-based bioenergy relate to four primary characteristics with respect to its raw materials (biomass residues), i.e., excessive removal from plantation fields which can affect soil fertility; valuation (relative to biomass products); competing uses (bioenergy, feed, fiber, fertilizers); and treatment of biogenic carbon (assumptions of carbon neutrality vs. complete inventory). These unique features require specific LCA approaches which vary from those of conventional product-based bioenergy.

The thesis is structured in the following manner. The five research questions are discussed and answered in the preceding Chapters 2, 3, 4, 5, and 6, respectively, and are further summarized in this section. Chapters 2 and 3 are not discussed further since the issues on the LCA of bioenergy, in general, and second generation bioethanol have been thoroughly presented in the respective chapters. Meanwhile, the proposed approaches that are analyzed in Chapters 4, 5, and 6 are further discussed in terms of potential application and additional required research in Sections 7.2 and 7.3. Overall, the thesis proposes the following approaches: solutions to the existing dissimilar practices in the LCI of biogenic carbon (Chapter 4); an LCIA method of removing biomass residues from soil on biomass productivity (Chapter 5); and methodological choices in comparative LCA of biomass residues utilization (Chapter 6). The answers to the research questions are listed below.

7.1.1 What are the key issues in conducting an LCA of bioenergy systems?

Key issues in conducting an LCA of bioenergy systems include the followings. Goal and scope definition is an important initial step since the choice of methodology used depends on the purpose of an individual study. These methodological choices include system boundary, functional unit, inventory data, and treatment of multi-functional processes (allocation). Within this category, there is also a debate between attributional and consequential LCA which, for bioenergy, is even more crucial than for ordinary products.

Bioenergy poses more methodological challenges than other types of renewable energy since the system boundary also incorporates agricultural phases to produce biomass feedstock. In this aspect, there is a question of how to properly treat biogenic carbon in terms of capture and emission flows in the inventory. In addition, agricultural processes lie in the intersection between environmental and economic systems. Meanwhile, LCA methodology has not been particularly unambiguous with regard to direct and indirect land-use changes, regional variability leading to regionalized impact assessment, and the choice of impact categories. These are challenges for further development of an LCA in order to improve analyzing a bioenergy system.

7.1.2 What is the environmental sustainability status of second generation bioethanol?

Despite the non-homogeneous system definition of the reviewed LCA studies, it was concluded that second generation bioethanol exhibits improved performances over fossil fuel for, at least, the two most studied sustainability aspects, i.e., net energy output and global warming. For the latter parameter, carbon sequestration at the biomass generation stage can consistently offset total GHG emissions from all elements of the life cycle chains at high ethanol percentage (≥85%).

The aspects of biogenic carbon and agrochemical input for energy crops and biomass residues and the effect of the removal of the latter from soil have not been addressed consistently. The bioethanol conversion process is primarily based on simultaneous saccharification and co-fermentation which is characterized by high yield and low energy input. In this regard, the LCA results tend to under estimate the actual impacts of current technology. The choice of allocation methods strongly influences the final results, particularly when economic value is employed as a reference. Substitution of avoided burden appears to be the most popular allocation method in practice, followed by partition based on mass, energy, and economic values.

It is believed that residue-based bioenergy will play more important roles in the global energy mix. Future exploitation of biomass residues is speculated to be driven mainly by emerging technology for second-generation bioethanol. This is a natural consequence of strive competition for the same raw materials (sugar, starch, and vegetable oil) between food and energy sectors.

7.1.3 How much would the final results of biogenic carbon neutrality assumptions deviate from the true values based on a complete inventory?

This study demonstrates that the global warming impacts of scenarios based on the LCA principles, treating all relevant input-outputs as genuine flows (including biogenic carbon), provides various results which are in many cases different from those assuming biogenic carbon neutrality (excluding biogenic carbon). In addition to the existing arguments of carbon stock change and carbon storage capacities of long-rotation trees or wood products, the current study supports the assertion that the assumption on biogenic carbon neutrality introduces biases to the 'true' values based on a complete inventory. The extent of such a bias, which can make the values of global warming impacts substantially higher or lower, depends on specific situations. Three factors are identified to substantially propagate biases in the evaluation of global warming performances of a bioenergy system. They are differences in framing system boundaries (cradle to grave vs. cradle to gate), forms of carbon emissions (CO_2 vs. CH_4), and valuation of biogenic carbon (biomass products vs. biomass residues). The results of this study are expected to contribute to the harmonization of future bioenergy LCA by directing further research to adopt more the concept of utilizing a complete inventory rather than the neutrality assumption.

7.1.4 How to assess the impact of removing biomass residues from soil on biomass productivity?

An impact assessment method relating the removal of biomass residues with soil organic carbon and net primary production has been developed. The assessment method was developed within the LCA framework based on a specific system definition, i.e., decomposed biomass residues above soil surfaces resulted in net carbon flow into soil compartments. In addition to GHG emissions into the atmosphere, the soil organic carbon functions as an additional elementary flow to complete the overall carbon balance. The assessment method considers the effects of soil organic carbon on soil biomass productivity as a midpoint indicator, which is expressed as a loss of net primary production. The impact assessment method is in accordance with the ISO-standard format, comprising a characterization factor and an input term representing changes in elementary flows:

$$(\Delta \mathrm{NPP})_{\%\mathrm{Removal}} = \left(\frac{\mathrm{dNPP}}{\mathrm{dSOC}}\right)_{\mathrm{Climate,\,Vegetation,\,Soil}} \times \frac{\mathrm{dSOC}}{\mathrm{d\%Removal}} \times \%\mathrm{Removal}.$$

The operation of the proposed method was illustrated with a moderate case study. It demonstrated that the method has genuine potential to be developed as metrics for assessing the sustainability of bioenergy systems. However, to operate the assessment model for a specific region, data for spatially detailed implementation within bioenergy systems in various regions need to be completed.

7.1.5 How to compare the impact of various treatment options on biomass residues in a palm oil system?

Guidelines for methodological choices in terms of system boundary, functional unit, and solutions to multi-functional problems have been proposed. The methods can be employed to systematically compare the LCA results of different treatment options and valuation of EFB in a palm oil system. Comparison based on the same multi-functional units can be accomplished only in cases where additional co-products were utilized internally. Based on a global warming impact, the mulch option was preferred among other treatments (compost, ethanol, treated in incinerator, and sold as coproducts). This conclusion requires further verification since results are extensively dependent on local inventory data. The effect of the avoided process of producing synthetic fertilizers and the assumption that all parts of mulch are available as soil nutrient dominantly determined the final result. The study also demonstrates that the status of EFB as waste or goods is influential on the final results if the EFB is employed externally but has no effect if it is utilized internally.

Knowledge regarding preferred alternatives for managing biomass residues like EFB could improve environmental performances and orient towards best practices. Further studies incorporating a site-specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines. Besides palm oil systems, the approach is also readily applicable to biomass residues in other agro-based industrial systems.

7.2 Potential applications of the proposed approaches

Although LCA methods in general have already significantly advanced for describing the sustainability of bioenergy systems, there are still additional questions to be answered for residue-based bioenergy. The overall framework of the thesis was designed to develop an approach to compare the impacts between leaving biomass residues in fields or utilizing them for bioenergy. It also offers an approach to distinguish methods of handling biomass residues differently from biomass products in bioenergy systems. The potential applications of the proposed approaches encompass certain aspects of environmental sustainability assessment as discussed below.

The primary contribution of Chapter 4 is the re-evaluation of the widely applied biogenic carbon neutrality assumption in scientific literature. In addition to the existing arguments of carbon stock change (Searchinger et al., 2008) and carbon storage capacities of long-rotation trees (Cherubini et al., 2011) or wood products (Levasseur et al., 2012), the current study supports the assertion that the assumption on biogenic carbon neutrality introduces biases to the ‘true’ values based on a complete inventory. Therefore, the recommendation to the existing dissimilar practices with biogenics is to treat carbon flows as genuine flows, i.e., not assuming carbon neutrality. In this respect, all input-output flows based on the entire life cycle of a product system are to be included in the inventory. The results of this study are expected to contribute to a more harmonized bioenergy LCA in the future. Considering its broad spectrum of implementation in the field of bioenergy, the potential users of this proposed approach include LCA researchers, practitioners, and policy makers.

Previous studies regarding the removal of biomass residues have focused only on the impact of GHG emissions into the atmosphere. To complete the carbon balances, more recent development also considered the effect of carbon flows into the soil matrix, i.e., an integrated assessment of impacts on global warming and SOC (Liska et al., 2014; Mckechnie et al., 2011; Repo et al., 2011, 2012; Guest et al., 2013). Additionally, Milà i Canals et al. (2007) and Brandão and Milà i Canals (2013) have further addressed the relationship of SOC and biomass productivity. Likewise, this thesis also models the effect of removing biomass residues on the flow of organic carbon into the soil matrix which alters the SOC content and subsequently leads to the loss of biomass productivity. Compared to the previous studies, the novelty of the approach is that the impact is expressed in terms of a characterization factor and an input term representing changes in elementary flows. Although the method in Chapter 5 has been developed for bioenergy systems, it is also appropriate for other product systems involving the removal of biomass residues from soil since the characterization method provides a general framework of converting elementary flows (soil organic carbon, SOC) into an impact (net primary production, NPP). Considering that the method is formulated in a somewhat generic form, perhaps it can provide direction to LCA researchers and developers for further development.

To be able to properly compare and interpret the results of different studies, an assessment framework to evaluate biomass residues in a specific agro-based industrial system is necessary. For example, previous LCA studies in a palm oil system indicate a broad range of global warming impacts from net positive (GHG emissions) to net negative values (GHG savings) (Stichnothe and Schuchardt, 2010; Lim and Lee, 2011; Hansen et al., 2012). These results, however, are not practically comparable since the scores were not based on the same functional units. In this regard, the proposal in Chapter 6 contributes to harmonizing the approaches for conducting LCAs of biomass residues in a palm oil system so that the results could be compared. The proposed methodological choices encompass system boundary, functional unit, and solutions to multi-functional problems. Although the approaches were illustrated for a palm oil system, they are also readily applicable for managing biomass residues in other agro-based industrial systems since biomass residues generated in agricultural phases or post-harvest processing units are considered as co-products which are all included in the inventory. These various co-products are considered as an economic output with different functions or values. Considering the practical nature of the proposal, the potential users of this approach are LCA practitioners and researchers.

7.3 Areas of future research

In spite of the potential application of the proposed approaches, additional research is still required to elaborate a number of embedded problems. One of the major issues is in regard to the primary function of biomass residues in agricultural fields. Naturally, their stock of nutrients provides a basic recycling mechanism that maintains soil fertility. They can also improve the structure of soil for enhanced aeration and water management. Excessive removal of biomass residues may degrade soil quality and also potentially influence future crop yields (Wilhelm et al., 2004; Lal, 2005; Cherubini et al., 2009). This could be a serious detriment to the long-term sustainability of residue-based bioenergy and should, therefore, be considered as a component of the sustainability assessment. One of the key solutions is to compensate the substantial nutrient export with inorganic fertilizers. However, this option may create further consequences on environmental and financial cost that must be carefully evaluated.

Bioenergy poses an increasing number of methodological challenges more so than other types of renewable energy since the system boundary also incorporates agricultural phases to produce biomass feedstock. The problem is that agricultural processes lie in the intersection between environmental and economic systems. Meanwhile, the existing LCA methodology has not been particularly unambiguous with regard to direct and indirect land-use changes, local variability leading to regionalized impact assessment, and the choice of impact categories. These are challenges for further development of the LCA in order to better analyze a bioenergy system.

Required research related to additional development of the proposed approaches is described below. The results presented in Chapter 4 require proper interpretation since they are based on certain hypothetical inventory data. Further analysis exploiting actual inventory data, for example, those available in literature, may be necessary to further verify if the assertion for the non-neutrality assumption of biogenic carbon is also valid for other inventory situations.

The primary issue in the implementation of the proposed method in Chapter 5 is locating specific data on bioenergy systems that demonstrate the relationship between biomass removal at different rates on the states of SOC and NPP. Data unavailability is the main reason why the illustrated example did not utilize data from a bioenergy system but, instead, from a grazing system. Additional extensive research is necessary to accordingly determine the effect on future biomass productivity from removing biomass residues from various regions. These data are necessary for developing specific characterization factors for impact assessment in certain regions. This effort would be even more relevant in the near future considering the substantial advancement in the research and development on second generation bioethanol.

The conclusion in Chapter 6 regarding mulch being the most appropriate treatment option requires further verification since the study was based on the assumption that all parts of the EFB were available as soil nutrient. In reality, some elements would experience aerobic and anaerobic degradation and emit GHGs into the atmosphere. Therefore, proper mass balances on biomass decomposition processes in fields which include carbon flows into the atmosphere and soil matrix are required. In addition, the inventory models were based on processes available in the Ecoinvent database. Further studies incorporating a site-specific case of palm oil systems would better illustrate the usefulness of the proposed guidelines.

7.4 Concluding remarks

An optimistic estimate suggested that, by 2050, bioenergy could sustainably contribute up to one third of the global primary energy supply from the current state of approximately only ten percent (IEA, 2009). More specifically, residue-based bioenergy is speculated to increase its key role in the future energy mix as a consequence of the harsh competition between food and energy sectors over the same raw materials (sugar, starch, and vegetable oil) (IPCC, 2011). This competition has encouraged the exploitation of non-food resources which are so far still dominated by fuel wood for traditional cooking (IPCC, 2011). This fact demonstrates that there continues to be significant opportunities for improved biomass utilization for bioenergy that is more efficient and environmentally friendly. This trend would likely be enhanced by the advancement in research and development on emerging conversion technology such as second-generation bioethanol. In line with this trend, potential biomass residues as bioenergy feedstock are abundant and available in many different regions worldwide. The global production of just crop residue can reach 3.8 billion metric tons annually, which is equivalent to a total energy of 70 EJ (Lal, 2005). These resources, however, must be diligently managed since, in addition to bioenergy, biomass residues also play many other competing roles. In particular, residues generated in fields naturally contribute to maintaining soil fertility and future harvests. Meanwhile, those generated in post-harvest facilities may also be used as fertilizers, feed, fibers, or other biorefinery feedstocks. In this regard, the contribution of the thesis is to propose guidelines to be able to determine, among the various potential uses of biomass residues, which options would have the least environmental impacts.

An LCA can influence the future of residue-based bioenergy provided that the method is formulated accordingly, referring to the specificity of the feedstock. It is an environmental assessment tool for a product system which differentiates the status of an economic flow associated with a unit process as goods or waste. The problem is that many studies on the LCA of residue-based bioenergy have not clearly defined the economic status of the biomass feedstock. Perhaps this is due to the difficulty in deciding whether the price of a residue is positive or negative. Meanwhile, in theory, proper identification of an economic status of input flows to and output flows from a unit process is required as it will consequently influence how an LCA should be conducted. This thesis offers an approach for residue-based bioenergy to be managed accordingly that is different from that for product-based bioenergy.

Although a number of improvements have been suggested, sustainability of bioenergy cannot be comprehensively evaluated by only utilizing LCA. It requires other complimentary analyses because sustainability of bioenergy systems encompasses a wide variety of parameters including environmental, economic, and social aspects. Under these three pillars, GBEP (2011), for example, established twenty four sustainability indicators for bioenergy which are more than the number of impact indicators typically employed in LCA.

Another relevant development on the sustainability assessment of bioenergy is an effort to assess production and consumption aspects of a product system in an integrated manner. In that regard, Heijungs et al. (2014) proposed incorporating the concept of planetary boundaries (Rockström et al., 2009) in an LCA framework to appraise sustainability. This innovative approach, so called backcasting LCA (Guinée and Heijungs, 2011), assesses not only environmental impacts, as in a conventional LCA, but also specifies consumption levels of a product that are appropriate within the limits of environmental sustainability.

7.5 References

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