Development of life cycle assessment for residue-based bioenergy

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Chapter 5

A novel life cycle impact assessment method on biomass residue harvesting

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Abstract

Second generation bioenergy such as cellulosic bioethanol is expected to become commercially available in the near future. Large scale production of this bioenergy will require secure and continuous supplies of raw materials. One promising source of materials is biomass residues that currently remain on the fields following harvest, a feedstock that does not compete with food. However, unsustainable removal of these residues may adversely affect soil quality and hamper future harvests. In order to assess this effect, an impact assessment method was developed within the life cycle assessment framework based on a specific system definition, i.e. decomposed biomass residues above soil surfaces resulted in net carbon flow into soil compartment. This soil organic carbon functions as an elementary flow to complete the overall carbon balance. The assessment method considers effects of soil organic carbon on soil biomass productivity. This impact is expressed as loss of net primary production, a midpoint indicator. The impact assessment method follows the ISO-standard format, comprising a characterization factor and an input term representing changes in elementary flows. The operation of the proposed method was illustrated with a small case study. At 10% biomass removal, the impact is 7.16 g-carbon/m^2.year loss in biomass productivity as compared to the undisturbed reference. We believe that the method has a good potential to be adopted and employed as metrics for assessing the sustainability of bioenergy systems, although data for spatially detailed implementation within bioenergy systems in various regions are to be supplemented.

Keywords
Life cycle impact assessment, Bioenergy, Biomass residue, Biomass productivity, Soil organic carbon, Global warming.

5.1 Introduction

When considering bio-based energy production, current LCA linked methods have a number of shortcomings: namely, they do not relate to biotic processes and they are not systematically linked to climate impacts. Methods to determine the effect of removing biomass residues from soil for example are now increasingly recognized as an important component in LCA studies. However, these effects are often ignored because they are difficult to quantify. We develop a number of improvements to better characterize the impact of using these residues as feedstock to generate cleaner biobased energy.

Feedstocks for bioenergy systems are principally based on woody biomass of forestry or agricultural residues, while only a minimal portion is derived from sugar, starch, and vegetable oil (IEA, 2009). Concerns regarding the competition with the food sector on a global level have encouraged the utilization of non-food resources as bioenergy feedstocks (IEA, 2009). A potential source for this purpose is biomass residues. Lal (2005) defined them as the non-edible portion of plants that remain on fields following harvest. These residues are differentiated from biomass products (e.g. energy crops) as they are in most cases not intentionally produced for energy resources (Cherubini et al., 2009). This biomass, therefore, could be exploited to increase the share of renewable energy mix that is targeted by many countries (Sorda et al., 2010) with a possibility of minimal environmental risks. Despite this optimism, there is an ongoing debate regarding the feasibility of removing crop residues from soil, particularly when complying with the allowable rates that continue to sustain agricultural systems (Cherubini et al., 2009; Lal, 2005; Wilhelm et al., 2004). The main concern is the potential impacts on degradation of soil quality that may further influence future crop yields. As for the technological status of bioenergy conversion, certain advanced processes, such as cellulosic bioethanol production, are relatively immature and continue to require further development to demonstrate profitable operations at commercial scales (Dale, 2011; IEA, 2009; Schnoor, 2011). However, some countries plan a substantial increase in the contribution of cellulosic ethanol in their energy mix. The United States for example aims at producing 16 billion gallon cellulosic ethanol in 2020 (Schnoor, 2011). When such new biofuel processes become technically and commercially feasible in the near future, a sudden increase in the demand for raw materials will certainly occur. Such situation may encourage import of biomass residues from other parts of the world, and farmers may become more willing to sell their residues for economic benefit.

Significant quantities of lignocellulosic biomass in crop residues are available in many regions of the world and, therefore, possesses great potential as a feedstock for bioenergy (IEA, 2009). Global production of crop residues in 2001 was estimated at 3.8 billion metric ton annually with a total energy value of 70 EJ (Lal, 2005). This potential share of lignocellulosic biomass as a feedstock for second generation bioenergy is obviously of strategic importance. The International Energy Agency (2009) recommends the biomass residues as one of the pivotal resources for sustainable bioenergy. However, the availability of these biomass residues is limited due to other competing uses such as feed, organic fertilizer, orfiber. For example, in the United States, corn stover is customarily exploited as a fodder. In addition, biomass residues fulfill an important role for agricultural lands. Their stock of nutrients provides a basic recycling mechanism that keeps soils fertile, and they improve the structure of the soil for improved aeration and water management. Excessive removal of this inflow of biomass, therefore, creates a risk of the degradation of soil quality. This can be a serious threat to long-term sustainability of second generation bioenergy systems and should, therefore, be considered as part of the sustainability assessment in terms of the harvested fraction in agriculture and forestry. Additionally, the biomass potential of crop residues is not fully available for bioenergy production due to the other competing uses. The fundamental questions in this research are: (1) what fraction of biomass is readily available as an additional feedstock for bioenergy? and (2) what would be the environmental impact if such amount of biomass is to be harvested from soil?

5.1.1 LCA studies on the removal of biomass residues

Life cycle assessment (LCA) studies of bioenergy systems were initially focused on the environmental impact assessment of feedstock cultivation originating from food-related products and energy crops (Cherubini and Strømman, 2011). Successively, more attention has been directed toward biomass residues left on fields (Cherubini and Ulgiati, 2010; Cherubini and Strømman, 2011). However, a recent review on LCA studies of second generation bioethanol concluded that the residues were treated inconsistently and that the divergence in LCA outcomes with this type of feedstock is much more significant than in LCAs on crop products or wastes (Wiloso et al., 2012). The surveyed LCA studies were often assumed to employ only the surplus biomass or to consider a greater fraction of residues but with fertilizer compensation to maintain soil fertility. In certain forest and crop management practices in which residues are burned following harvest, it was assumed that removal of the biomass residues will not significantly alter the carbon entering the soil carbon pool (Cowie et al., 2006). Considering these variations in residue treatment and significant divergence in LCA outcomes, development a comprehensive LCA method for evaluating impacts on soil quality is warranted.

Most of the modeling studies in literature presented results on forestry cases with the exception of the crop residue cases presented by Cherubini and Ulgiati (2010) and Liska et al. (2014). The first authors proposed a lump parameter, the 'land use change', as the summation of reduction in soil organic carbon (SOC), methane emissions, and nitrous oxide emissions, among others. This parameter was determined to be significantly important, contributing to approximately half of the overall greenhouse gas (GHG) emissions. Liska et al. (2014) reported that removing corn residue from soil can reduce soil carbon and increase CO_2 emissions. Mckechnie et al. (2011) integrated emissions from forest carbon stocks and downstream bioenergy systems into the analysis. They concluded that ethanol produced from standing trees increased overall GHG emissions within a 100 year time frame while that from biomass residues reduced GHG emissions after a 74 year delay. Repo et al. (2011, 2012) described the impact of bioenergy systems in terms of decreasing carbon stock of the forest floor due to removal of biomass residues. They concluded that an improved global warming mitigation technique such as faster exploitation of decomposing residues (e.g. branches) would result in fewer 'indirect emissions' relative to slower decomposing residues (e.g. stumps). Further, Guest et al. (2013) modeled global warming impact as a function of the growth rates of plant biomass. In a typical long rotation forest ecosystem, the biomass residues could contribute between 44% and 62% of the overall CO_2 emissions (Guest et al., 2013). The results of the above mentioned studies on global warming impact have already integrated the impact on SOC stock. In contrast, Milà i Canals et al. (2007b) and Brandão and Milà i Canals (2013) have addressed the relationship of soil organic carbon and biomass productivity. In this regard, the current research models the effect of removing biomass residues on the flow of organic carbon into the soil matrix, which changes the SOC content, leading to the loss of biomass productivity.

5.1.2 Impact indicators for soil biomass-productivity

Ecosystems provide society with goods (e.g. food, fiber, and energy) and services (e.g. climate regulation, water and nutrient cycles, soil fertility, and photosynthesis) (MEA, 2005). In this regard, the loss of ecosystem functions may be represented in terms of various impact indicators such as the loss of soil fertility, biodiversity, or Net Primary Production (NPP) (Milà i Canals et al., 2007a). The last indicator is defined as net photosynthesis, or gross primary production (GPP) minus plant or autotrophic respiration, which is equivalent to above- and below-ground living plant biomass (IPCC, 2003). The NPP can be physically measured in the field or estimated by geographic information system (GIS) and remote sensing methods (Crabtree et al., 2009; Daughtry et al., 2005; Lu, 2006). GIS and remote sensing methods can estimate the amount of above-ground biomass over relatively extensive agricultural areas while direct field-measurement may only be practical in limited areas.

Previously proposed LCA frameworks regarding the aspects of ecosystem functions of land use have principally concentrated on three indicators: biodiversity (Koellner and Scholz, 2007; Milà i Canals et al., 2007a), soil quality (Milà i Canals et al., 2007b), and NPP (Lindeijer, 2000). Van der Voet (2002) and Lindeijer (2000) have suggested employing the NPP indicator to evaluate the ecosystem functions of soil to provide biomass. Milà i Canals et al. (2007a) employed Biotic Production Potential (BPP) which is defined as the ability or capacity of an ecosystem to sustain future biomass production depending on particular land use and sensitivity of the ecosystem. This concept is slightly different from the NPP which is more related to present biomass production capacity as a result of particular land use (Brandão and Milà i Canals, 2013). An additional relevant parameter is Net Ecosystem Productivity (NEP) which is largely adopted in forest-related studies (Cherubini et al., 2012; Luyssaert et al., 2007, 2008). It is defined as the difference between NPP and carbon released through soil or heterotrophic respiration (decomposition of 'dead' biomass) (Luyssaert et al., 2007, 2008). This study employed NPP rather than NEP since the effect of biomass residues removal was described in term of SOC as an intermediate indicator. Both parameters appear in the equations and are required in order to operate the impact assessment method.

5.1.3 Objective and structure of the paper

This research focuses on developing an impact assessment method to estimate the impacts of removing biomass residues from soil on the loss of biomass productivity, a midpoint indicator, employing SOC as an elementary flow input. The harvested biomass becomes a co-product of the specific bioenergy LCA.

The remainder of the article is presented in the following manner. In the methods section, the basic assumptions and development of impact assessment methods are presented. In the results and discussion section, the implementation of the proposed method is subsequently illustrated exploiting available data from the literature. Finally, sources of uncertainties, removal scenarios, and further implementation are discussed.

5.2 Methods

In this section, possible scenarios on the removal of biomass residues from soil and the effects on soil quality are described. Further, relevant impact indicators leading to the loss of biomass productivity are presented as an environmental pathway. Finally, impact assessment methods are developed based on system definition and assumptions.

5.2.1 Removal scenarios

This paper utilized IPCC (2003) in defining carbon pools of a soil system. This includes above- and below-ground living biomass, above-ground dead organic matter (wood and litter), and soil (SOC). In this context, SOC refers to organic carbon contained within the mineral horizons of soil while those above the soil surface are considered as the separate carbon pool of dead organic matter. Biomass residues were referred to those originating from agriculture, forestry, grasses, or post-harvest processing units. Excessive removal of these residues may cause a decline in SOC and consequently, biomass productivity.

In order to maintain sustainable agriculture, nutrient supplement in the form of additional fertilizer may be required depending upon soil type, humidity, and other local conditions. In this regard, a sustainable supply of the feedstock is defined as a condition where biomass is sufficiently produced to meet the present demand while soil fertility is maintained to secure future harvests. From an LCA perspective, there are three possible scenarios as to the level of impacts of removing biomass residues from soil:

1) removing only the actual surplus amount with negligible soil carbon degradation;
2) removing a larger fraction with fertilizer compensation; and
3) removing a larger fraction without fertilizer compensation, reducing soil carbon to levels with lower biomass productivity.

The first scenario is unambiguous as the surplus biomass-residues can be perceived as free goods bearing no significant environmental burden (levels of SOC and biomass productivity are maintained). The second scenario is more a shift of impacts on biomass productivity to an inventory issue, i.e. the production of additional fertilizer consequently leading to conventional impacts such as global warming, eutrophication, or acidification. The inorganic fertilizer is added to supplement the limiting nutrients (such as nitrogen and phosphor) contained in the removed biomass-residues while carbon is captured from the atmosphere through photosynthetic processes during plant growth. The third scenario would likely lead to a loss in SOC and biomass productivity due to unsustainable removal practices.The actual amount of the harvested residues is greater than the allowable removal rates with no balanced fertilizer compensation.

The terms “surplus” and “larger fraction” are used only to qualitatively define different scenarios. It is the proposed impact assessment method as an analytical tool to quantitatively determine the extent of biomass removal that affects SOC and subsequently biomass productivity.

5.2.2 Inventory aspects

In LCA, land use related processes, in general, lack a clear flow character as input or output components of a typical production system (Udo de Haes, 2006). The same problem is encountered in describing processes related to the degradation of soil quality. This parameter is also inadequate in terms of representative aggregate indicators, characterization factors, and data availability (Milà i Canals et al., 2007a). These are the main challenges in describing inventory aspects of biomass residues left on fields. However, if data on stabilized soil indicators of a certain region (such as SOC and NPP) could be made available, such information could be utilized to assess the consequences of removing parts or all biomass residues from the soil.

Various types of bioenergy feedstocks (biomass products or biomass residues) are characterized as having different environmental burden attribution schemes and impact categories. Land use related processes, in general, can lead to a number of impact categories such as global warming, eutrophication, acidification, toxicity, and others. These conventional impact categories, however, will not be the subject of further discussion in the current research. Instead, focus will be placed on impacts related to the states of SOC and biomass productivity. In general, land use impacts have been perceived as not only depleting physical surface areas (m^2.years of land use) but also altering land quality (Milà i Canals et al., 2007b). In this latter case, land is perceived as a distinct environment compartment, and elementary flows into the soil matrix can be considered as an environmental intervention. In this research, we are more interested in the aspect of quality degradation due to environmental intervention, so that depletion of SOC can be systematically linked to GHG emissions. The expanded system boundary (fields and bioenergy plants) and relevant elementaryflows to air and soil compartments are indicated in Figure 5.1.

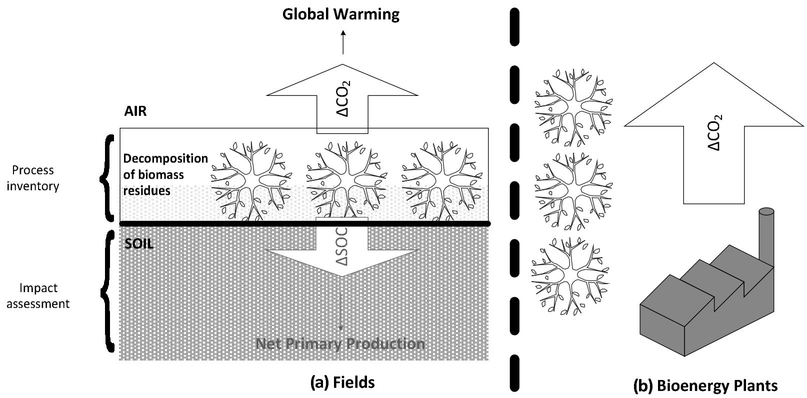


Figure 5.1. Effects of removing biomass residues on SOC and CO_2 flows at two contrasting situations: all residues are (a) left on fields and (b) removed for bioenergy production. Reduction in ΔSOC input leads to loss in biomass productivity. Carbon balance of an expanded system: $(\Delta CO_2)_{fields}+(\Delta SOC)_{fields}=(\Delta CO_2)_{bioenergy}$. The focus of this study is the assessment of the elementary flow taking place in soil compartment, indicated in red color. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article).

Under the IPCC accounting rules (IPCC, 2006), countries separately report their emissions from energy use and from land use change. For example, if a hectare of forest is cleared, the carbon depletion from the forest is considered as a land use emission. If the wood is then exploited for bioenergy, the regulations allow countries to ignore the same carbon when it is released after combustion in order to avoid double-counting. In other guidelines or databases such as EU-Directive (2009) or Ecoinvent database (2010), for example, both emissions in the field and in the bioenergy system are considered, but their values are somehow similar, $(\Delta CO_2)_{fields} \approx (\Delta CO_2)_{bioenergy}$, resulted in zero net emissions. Referring to Figure 5.1, these guidelines and database considered GHG emissions at different system boundaries but failed to recognize the significant elementary flow of organic carbon into the soil matrix. These two distinct elementary flows to two different environmental compartments (air and soil) are, in fact, taking place simultaneously, as illustrated in Figure 5.1. From an LCA perspective, this SOC flux must also be taken into consideration during the inventory process. Therefore, in the current research, this 'missing' elementary flow (SOC) was included to complete the carbon balance of relevant processes occurring within the pile of biomass residues on soil surfaces. The complete carbon balance of the GHG emissions and organic carbon flows at the expanded system boundary (field and bioenergy plants), therefore, can be expressed as $(\Delta CO_2)_{fields}+(\Delta SOC)_{fields}=(\Delta CO_2)_{bioenergy}$. This additional elementary flow was further employed to evaluate the impact that removing biomass residues has on biomass productivity of the affected soil.

Biomass residues left on fields experience certain processes that are governed by natural and human factors. The main natural process is decomposition of the biomass in which intensity is affected by human intervention. The intervention is in the form of extracting biomass residues at a certain rate from the fields to a bioenergy plant (see Figure 5.1). A larger fraction of biomass removed from the field will certainly reduce the amount of biomass experiencing the decomposition process and, consequently, the organic carbon flows into the soil matrix. To translate these processes into an LCA framework, the system boundary can be defined as piles of biomass residues situated on top of soil. Within these piles, a natural decomposition process occurs, which converts organic biomass into simpler forms of organic carbon and further into CO_2 or CH_4. These degradation products are then simultaneously released as organic carbon flows and emitted as GHGs at different environmental interfaces, biomass-soil and biomass-air, respectively (see Figure 5.1). The effect of such processes on carbon pools has recently been modeled by Guest et al. (2013) for changes in CO_2 emissions and Repo et al. (2011, 2012) for changes in carbon stocks. The decomposed biomass residues deliver organic carbon into the soil matrix, providing nutrients and other qualities that improve soil quality. This elementary flow results in a different impact category, i.e., soil biomass-productivity represented by NPP, a midpoint indicator. This research, therefore, complements and improves previous studies of similar systems by using a different impact category.

5.2.3 Environmental pathways of impact indicators

Biomass production capacity is affected not only by local climates and soil types but also by processes that occur in living vegetation (McBride et al., 2011). In this research, the parameters having the greatest influence on NPP are integrated into a cause-effect chain of an impact pathway as demonstrated in Figure 5.2. Endpoint impacts on human and ecosystem health are included only to illustrate their relationship with NPP, a midpoint indicator. In order to comprehend the complex nature of NPP as an impact indicator, this section describes some of the factors that are influential to SOC and biomass-productivity. For example, in second generation bioenergy systems, raw material in the form of lignocellulosic biomass is supplied mainly from an agricultural chain. Therefore, the fertility of the soil where the biomass is produced plays a key role. According to Sleeswijk et al. (1996), one manner to evaluate soil resources is by monitoring its degradation process. This can be evaluated in terms of dynamic properties of the soil over time (Anton et al., 2007). Soil conditions are affected not only by the natural condition of the ecosystem but also by the activities subjected by it (Mattsson et al., 2000; Sleeswijk et al., 1996). Those induced by human activities include land management, agricultural inputs, and biomass harvest including the extraction of biomass residues from the soil. Factors of natural origin include soil types (sandy, clay, peat), local climates (arctic, temperate, tropic), and processes occurring in living vegetation such as photosynthesis and respiration.

A single aggregate indicator for soil quality is not easily established due to numerous soil characteristics and their complex interactions with agricultural practices (Garrigues et al., 2012). Disregarding this difficulty, Milà i Canals et al. (2007b) have initiated exploiting soil organic matter (SOM) as the sole indicator of soil quality, which is represented as SOC. The current research is in accordance with this approach and employs SOC to represent the state of soil quality. This is supported by McLauchlan (2006) who stated that SOC, in many ways, dominantly regulates soil moisture, structure, nutrient, and microbial activity. Otherwise stated, the SOC performs a central function in determining the state of soil quality. Based on this perspective, the current research assumed SOC as the dominant factor influencing biomass productivity.

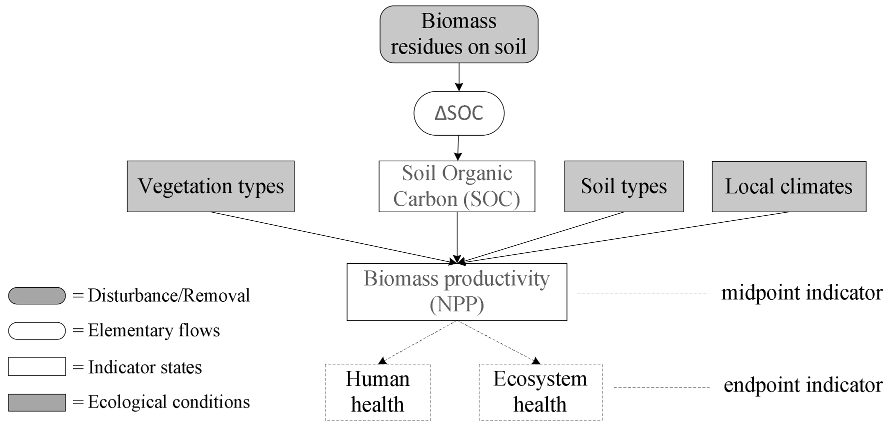


Figure 5.2. Environmental pathways of impact indicators with ΔSOC as an elementary flow input. (Endpoint impacts on human and ecosystem health –dashed arrows and boxes– are included only to show their relation with the NPP as a midpoint impact indicator).

However, there are some exceptions to the above rule. For example, in the case of peat soil consisting mainly of organic materials, the SOC is likely to be less dependent on the amount of above-ground biomass that is extracted from the soil. In contrast, the impact would be much more pronounced when the removal occurred in clay soils where the SOC has a strong correlation with external carbon inputs. In addition to the above-ground biomass as the source of carbon inputs, roots can also contribute to more than half of the SOC depending on the types of vegetation (Wilhelm et al., 2004). In this last case, the state of the SOC is also likely to be less sensitive to different biomass removal rates. These different conditions may explain why most studies could not agree on the allowable removal rates that do not affect soil quality and biomass productivity (Lal, 2005; Wilhelm et al., 2004). Considering the above deviations from the main assumptions, the proposed model can be regarded as a simplification of the actual situation. The impact assessment method can be beneficial for practical reasons and regarded as an initial proposal until an improved alternative becomes available.

Ecological processes affecting soil quality (represented as SOC) and soil biomass-productivity are described in the following. Soil organic matter comprises residues of plants and animals decomposing by microorganisms at any stage (Cowie et al., 2006). The process of organic mineralization results in carbon (CO_2, CH_4) and nitrogen emissions to the atmosphere and simultaneously provides nutrients for plants to grow. Such a decomposition process is enhanced in warm and moist climates (tropical) and reduced in low temperature and limited moisture regions (temperate and arctic) where microbial activities are inhibited. Therefore, soil carbon stocks are typically lower in the wet tropics where organic matter is quickly cycled and lowest in dry environments where plant growth is limited (Cowie et al., 2006). The rate of mineralization is also influenced by the chemical composition of residues. Residues with low nitrogen content or a high portion of the recalcitrant component such as lignin has the lowest rate. In addition, soil with significant clay content better preserves nutrients than that of sandy soil due to improved absorption performances. For example, soil carbon stocks are high in soils with high-activity clay (e.g. Andisols, Vertisols, Mollisols), followed by low-activity clay soils (Oxisols, Ultisols) and low in all sandy soils (Cowie et al., 2006). Other important aspects of soil quality are soil salinization, soil compaction, soil erosion, and biodiversity (Garrigues et al., 2012). These natural states can affect soil organic matter in various ways as increases or losses (Garrigues et al., 2012; McLauchlan, 2006), but were not specifically included in the characterization factor of the current study.

5.2.4 Development of the impact assessment method

The changes in organic carbon flows due to biomass removal at different rates will lead to a reduction in SOC and a loss of biomass productivity at different levels. As demonstrated in the environmental pathways (Figure 5.2), organic carbon flows into the soil matrix are categorized as elementary flows while the concentration of SOC and level of NPP are categorized as indicator states. These parameters (organic carbon flows, concentration of SOC, and level of NPP) were employed as the basis to develop the impact assessment method. The generic expression of an impact assessment method for a midpoint indicator is expressed as:

$$\text{Impact} = \text{CF} \times \text{Input} \qquad (5.1)$$

Equation (5.1) comprises a characterization factor (CF) and an input term representing changes in elementary flows. The CF depicts the impact assessment step while the term input represents the results of a process inventory. The CF is correlated with the upstream activity, extraction of biomass residues, and, with the downstream indicator, soil biomass-productivity. This type of expression is in accordance with the formulation of an impact assessment method suggested by the ISO standard (ISO, 2006) as the linear product of inventory results and characterization factors. A similar expression of impact assessment models has been utilized by Van Zelm et al. (2007) for various impact categories, for example, loss in biodiversity due to acidification processes. More specifically, the characterization factor is formulated as the following:

$$\text{CF} = \frac{\text{dNPP}}{\text{dSOC}} \qquad (5.2)$$

where NPP is the net primary production in g-carbon/(m^2.year). The dNPP is the change in the amount of carbon contained in living biomass as a consequence of removing biomass residues from soil. The dNPP is illustrated later in Figure 5.3 (b) as the difference between two points within the fitted line. SOC represents the concentration of organic carbon in a soil layer of certain depth. Even though the concentration of SOC in a unit volume of soil is expressed in g-carbon/m^3, it is established practice to choose a fixed top layer depth, and express the SOC per unit area, in g-carbon/m^2 (Milà i Canals et al., 2007b; Brandão and Milà i Canals, 2013; IPCC, 2006). We follow this practice, thus expressing our characterization factor in year^{-1}. The soil layers in the study conducted by Wang et al. (2008) for example were between 20 cm and 30 cm, while IPCC (2006) used 30 cm deep as the default value.

The two differential terms (dNPP and dSOC) in the CF describe the changes in SOC and NPP due to biomass removal from fields. This suggests that the data required are only the instant/immediate changes as a response to human disturbance with the removal of biomass residues from soil. Therefore, the area of application of the method can be rather general. For example, it could be applied for both forest and agricultural systems. The characterization factor is formulated in terms of differential changes, a steady state approximation of a dynamic process. These changes represent responses in terms of magnitude of the impact to disturbances. A larger magnitude of impacts would be indicated with a steeper slope.

Biomass productivity not only depends on the level of SOC but also on variability in local climates, vegetation species, and soil types. These ecological factors must also be considered in order to obtain a more representative value in relationship to location-dependent aspects. In the current proposed model, local climates, for example, are categorized as arctic, temperate, and tropical while soil types are classified into sandy, clay, and silt. It is generally accepted that precipitation and temperatures are the main factors governing local climates which subsequently cause considerable spatial variation in SOC and NPP (McLauchlan, 2006). Vegetation types could be categorized as fast or slow growing species. Also, the type of roots (coarse or fine roots) and the ratio of roots (belowground biomass) to shoot (above-ground biomass) may affect the variability of the above parameters. Considering the above arguments, Equation (5.2) must be modified into:

$$\mathrm{CF} = \left(\frac{\mathrm{dNPP}}{\mathrm{dSOC}}\right)_{\mathrm{Climate,\,Vegetation\,,Soil}} \qquad (5.3).$$

Geographical variability regarding agricultural data is a common issue in an LCA of agricultural systems. This issue has been systematically incorporated into the characterization factor as ecological conditions in terms of climate, vegetation, and soil types. This expression of CF can serve as a generic platform to describe how local conditions may affect indicator states. Therefore, the values of the CF must be updated in accordance with the data regarding the effect of biomass removal on SOC and NPP in various regions.

The term input in Equation (5.1) is the difference in concentration of SOC as a function of flows of organic carbon entering the soil matrix. It can conveniently be expressed as $(\Delta\mathrm{SOC})_{\Delta\mathrm{Organic\text{-}Carbon}}$. The magnitude of this elementary flow is determined by the amount of biomass residues remaining on the soil following extraction for bioenergy or other purposes. This is in accordance with the environmental pathways illustrated in Figure 5.2. However, the organic carbon flow is not an easy parameter to measure, and such data are hardly available. To solve this problem, the changes of SOC concentration was expressed in terms of the percentage of removed biomass, i.e. amount of harvested biomass over initial amount of biomass, $(\Delta\mathrm{SOC})_{\%\mathrm{Removal}}$. Therefore, the working equation becomes:

$$\mathrm{Input} = (\Delta\mathrm{SOC})_{\%\mathrm{Removal}} = \frac{\mathrm{dSOC}}{\mathrm{d\%Removal}} \times \%\mathrm{Removal} \qquad (5.4)$$

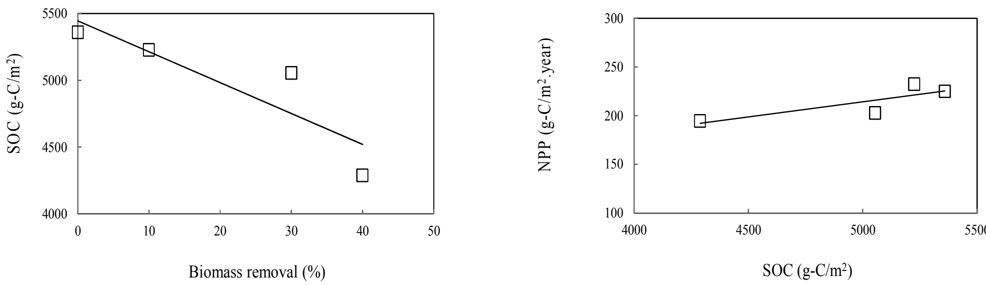
Considering all of the above equations, the proposed impact assessment method can be re-written as the following:

$$(\Delta\mathrm{NPP})_{\%\mathrm{Removal}} = \left(\frac{\mathrm{dNPP}}{\mathrm{dSOC}}\right)_{\mathrm{Climate,\,Vegetation\,,Soil}} \times \frac{\mathrm{dSOC}}{\mathrm{d\%Removal}} \times \%\mathrm{Removal} \qquad (5.5).$$

5.3 Results and discussion

5.3.1 Operation of the proposed method

The following example illustrates the operation of the proposed impact assessment method to assess the effect of removing biomass residues from soil. Figure 5.3 (a) and (b) were drawn based on simulation data of Wang et al. (2008) regarding the grazing system for livestock farming, meadow steppe dominated by *Leymus chinensis* in Songnen grasslands, Northeast China. The SOC and NPP responses to various grazing intensities were recorded over duration of 50 years of observation. The data point in the X-axis represents a 10 year average of 0%, 10%, 30%, and 40% grazing intensities. In this illustration, we did not include data at higher grazing intensity (60% and 80%) since the effect of biomass removal around these rates resulted in a very sharp decrease in NPP, indicating a non-sustainable agricultural practice. In this regard, Wang et al. (2008) suggested an optimal grazing intensity up to 40% in order to maintain the sustainability of *L. chinensis* grassland. Zero percent biomass removal signifies that all of the grass was left undisturbed in the field. Under this condition, the values of intact NPP and SOC were 225 g-carbon/(m^2.year) and 5444 g-carbon/m^2, respectively.



(a) (b)

Figure 5.3. (a) Effect of biomass removal on SOC, where SOC = (-2311 x biomass removal) + 5444, data points indicate the measured relationship between the extent of biomass removal and reduction in SOC; and (b) Effect of changes in SOC on NPP, where NPP = (0.031 x SOC) + 59.34, data points indicate the measured relationship between SOC and NPP. (based on data of Wang et al., 2008).

The grazing region comprises meadow Chernozem soil (35% clay, 45% silt, 20% sand), a semiarid temperate monsoon climate, and mean annual precipitation of 564 mm. Conditions of a pasture area, in many aspects, are similar to the case of biomass residues removal described in this current paper. This is mainly due to management operations of the pasture system being less demanding when compared to typical crop production systems. Therefore, agricultural inputs are minimal. If the mature grass is not harvested, it will, naturally, become litter and decompose, following a closed-loop nutrient cycle.

Assuming that the grassing scenarios presented by Wang et al. (2008) are equivalent to the removal of biomass residues for bioenergy systems and changes in the slopes indicate magnitude of impact to biomass residues removal (strong correlation), the data can be exploited as a basis to illustrate the derivatives of SOC and NPP at various rates of biomass removal. The effect of grazing intensities between 0% and 40% on SOC and NPP are depicted as slopes ((dSOC/d%Removal) and $(dNPP/dSOC)_{Climate,Vegetation,Soil\text{-}types}$ in Figure 5.3 (a) and (b), respectively. Following the parameters expressed in Equation (5.1), CF (dNPP/dSOC) represents the term for the impact assessment step while input (dSOC/d%Removal) represents the results of process inventory. Assuming that an effect of 0%–40% biomass removal on SOC and NPP are linear, as exhibited as straight lines in Figure 5.3 (a) and (b), the value of (dSOC/d%Removal) is –2311 g-carbon/m^2, and (dNPP/dSOC) is 0.031/year. Therefore, at 10% biomass removal, Equation (5.2) becomes:

$$(\Delta \mathrm{NPP})_{10\%} = \left(\frac{0.031}{\mathrm{year}}\right)_{\text{Temperate monsoon, Leymus chinensis, Chernozen soil}} \times -2311 \frac{\mathrm{g \cdot carbon}}{\mathrm{m^2}} \times 10\% = -7.16 \frac{\mathrm{g \cdot carbon}}{\mathrm{m^2.year}}.$$

It signifies that, at 10% biomass removal, the impact in terms of loss in biomass productivity is 7.16 g-carbon/m^2.year compared to the undisturbed reference. Otherwise stated, the biomass production capacity of the soil associated with the biomass removal at approximately 10% will reduce the carbon stock by 7.16 g for an area of one m^2 annually. Similarly, assessment at 20%, 30%, and 40% removal rates will result in biomass productivity loss as much as 14.33 g-carbon/m^2.year, 21.49 g-carbon/m^2.year, and 28.66 g-carbon/m^2.year, respectively.

The operation of the proposed impact assessment method has been clearly illustrated based on data published in the literature (Wang et al., 2008). The operation of the method is fairly straightforward. It indicates the types of the required data. Therefore, the example in pasture areas under various grazing patterns should be sufficient to illustrate the operation of the proposed method. It is expected that other studies in other regions with similar ecological conditions would show similar changes in carbon stocks.

5.3.2 Sources of uncertainty

There are at least three sources of uncertainties in the proposed impact assessment method. These are related to the model, spatial variability, and data variability. The model uncertainty refers to correlations among parameters, such as between removal rates and SOC (dSOC/dRemoval) or between SOC and NPP (dNPP/dSOC). As shown in Figure 5.3 (a), for example, the dSOC/dRemoval correlation shows non-linear responses at higher biomass removal rates thus creating a higher uncertainty. This kind of responses reflect actual processes taking places within soil systems, i.e. carbon flows into the soil matrix as a result of the decomposition of biomass residues. In this regard, a linear approximation by local derivatives was made over a sufficiently small interval. This approach may be seen by some as major limitation for modeling soil processes. However, in LCA, where small functional units are usual, such linear approximations almost always form the basis of characterization factors (Hauschild, 2005). For example, most toxicity processes (dose-response relationship) are non-linear, but default linearized derivatives were typically used (Crettaz et al., 2002). This approach is more often in agreement with the international standards by ISO (ISO, 2006) and ILCD (EC-JRC-IES, 2010) which use characterization factors as a linearized approximation. This is justified in case of small changes compared to background data, which is true for most functional-unit-based LCA studies.

Spatial distributions are described in terms of local climates, vegetation, and types of soil. It suggests that regional variability of the characterization factor is represented by only 3 ecological conditions. This is obviously a simplification of real situations. However, this classification is by no means strict. Rather, it could be expanded to accommodate more detailed geographical variations. The characterization factor serves as a generic platform to describe how ecological conditions may affect indicator states. They could be implemented at various spatial levels (local or regional), depending on data availability, also in relation to the spatial resolution of the inventory data. The characterization factor could also be employed to estimate spatial variability of different regions depending on data availability. Additionally, the proposed method is intended to describe only a static model, temporal variability is outside the scope of the study.

Uncertainty related to data is a typical issue in agricultural systems. In this regard, soil quality and biomass productivity depend on various ecosystem properties in complex dynamics. From a modeling perspective, not all of the other factors could be included in the method. For example, it is possible that, in certain vegetation types, a considerable fraction of NPP is in the fast-growing form of fine roots entering the soil carbon pool (Cowie et al., 2006). In this case, the contribution of underground biomass may be significant. Therefore, the effect of above-ground biomass removal on SOC may not be as sensitive as when the root to shoot ratio and turnover rates are minimal. Included in this category is variability in biomass decomposition rates which depends heavily on the physical chemistry of the biomass material such as content of less degradable lignin in stumps versus branches (Repo et al., 2011, 2012).

5.3.3 Removal scenarios

In this paper, three possible removal scenarios which require proper impact assessment were described. The focus is on scenario 3 (removing larger fractions without fertilizer compensation) which affects biomass productivity. The option of keeping NPP constant by removing only the surplus amount (scenario 1) or removing larger fractions with fertilizer compensation (scenario 2) would, theoretically, not result in a loss in biomass productivity. This is not an impact assessment issue but a different inventory specification. In the case of constant NPP, the scenarios 1 and 2 would still indicate a loss of SOC as a climate emission. However, this paper is not intended to suggest which option among the three scenarios is better. From an LCA standpoint, it is always an open question to determine the more acceptable option between scenario 2 and scenario 3, which one is more acceptable depending on a specific case of bioenergy systems. Without prior judgments, the proposed impact assessment method could provide additionally quantitative information on the choices of the best option among scenarios. Perhaps, other assessment approaches will cohabitate side-by-side to serve different paradigms.

5.3.4 Further implementation

The operation of the impact assessment method requires data on SOC and NPP. Databases on these parameters are available for certain regions. For example, some databases listed over 700 estimates of NPP worldwide for selected zones and vegetation types (Alexandrov et al., 1999). Recently, Koellner et al. (2012) standardized classification of land use types and regionalization of land use inventories. For other areas, further exploration could be performed since methods for measuring or estimating SOC and NPP are well established. Currently, the primary issues in the implementation of the proposed method on bioenergy systems are locating data demonstrating the relationship between biomass removal at different rates on the states of SOC and NPP (dSOC/dRemoval and dNPP/dSOC). Further, due to data availability, the illustrated example used data from a grazing system, not a bioenergy system. A validation step using proper data is still needed. This latter problem exists because advanced bioenergy technology such as 2nd generation bioethanol is still emerging. In the near future, when the technology becomes feasible on a commercial scale, additional research should be directed to address this issue so that relevant data would become more available.

Discussion on the proposed method is focused on bioenergy application, but the method is also distinctly appropriate for other product systems involving the removal of biomass residues from soil. This is the case since the characterization method provides a general framework converting elementary flows (SOC) into an impact (NPP). Therefore, if data on bioenergy systems are not available, the proposed model could still be useful for other product systems.

5.4 Conclusions

Biomass residues left on the fields following harvest is a promising source of bioenergy feedstock. Unsustainable removal of these residues may adversely affect soil quality and hamper future harvests. Methods to determine such impacts are now increasingly recognized as an important component in LCA studies. We developed a number of improvements to better characterize bioenergy systems. The proposed impact assessment method relates the removal of biomass residues with the soil organic carbon and net primary production. The method does not cover a cradle-to-grave life cycle of bioenergy systems, but one stage, the provision of biomass feedstocks.

Considering the straightforward operation of the method and data availability in the future, we believe that the proposed method has a good potential to be adopted and employed as metrics for assessing the sustainability of bioenergy systems. The method can be regarded as an initial proposal and an assistance in moving research frontiers on the characterization of bioenergy systems.

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