Residual Biomass: A Silver Bullet to Ensure a Sustainable Bioeconomy?

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Abstract
The transition to a bioeconomy is generally considered as a step towards increased sustainability. However, increased biomass production can have several negative impacts and as a consequence, many cultivated biomass resources are unsustainable, thereby counteracting the sustainability objective of the bioeconomy. One proposed alternative is the use of residual biomass: biomass that is not cultivated for the use in a bioeconomy directly, but is a waste product of other processes. Since residual biomass is not produced on agricultural land it appears to be a silver bullet for sustainable biomass supply. But is that really the case? This paper discusses conditions that determine whether the use of residual biomass is indeed sustainable. Based on an extensive literature review we conclude that residual biomass is not a silver bullet, but can contribute to sustainability under certain conditions. Most importantly, the consequences for sustainability of changing current use have to be evaluated. Residual biomass is only seldom purely waste and regularly fulfils other functions, such as maintaining soil quality or providing habitats. The benefits of extracting residual biomass for new applications, thus causing a resource use change (RUC), have to outweigh the loss of their former function. Furthermore, not all residual biomass uses contribute to sustainability equally. Applications should be optimized to achieve various sustainability goals. Advances can be achieved through adapting technologies and logistics and increasing synergies between biomass-processing sectors.

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1. Introduction

Global challenges, such as reducing human dependence on fossil resources and emissions of greenhouse gases (GHG) causing human-induced climate change, are drivers for the development of a bioeconomy, in which biomass replaces fossil resources in various supply chains. The importance of sustainability in the development of a bioeconomy is broadly recognized (Pfau, Hagens, Dankbaar, & Smits, 2014). However, it is heavily debated whether an increased use of biomass resources contributes to a more sustainable situation. If biomass demands cannot be met in a sustainable way, the sustainability objective of the bioeconomy cannot be reached. Especially negative effects on GHG emissions and ecosystems of land use change in favour of increased biomass production are noted (e.g. Searchinger et al., 2008). One strategy that is often proposed by researchers and policy makers to avoid negative impacts of increased production is the use of residual biomass. Since residual biomass does not have to be produced on agricultural land, the initial assumption is that through avoiding land use change it is a sustainable alternative to biomass crops. Furthermore, it is generally assumed to be cheaper than cultivated biomass. All in all, residual biomass use appears to be an effortless, immediate and fail-safe solution to a complex problem for sustainable biomass supply. But can residual biomass really be the "silver bullet" enabling a sustainable bioeconomy?

The goal of this paper is to discuss conditions that determine whether use residual biomass contributes to sustainability. First, biomass supply and demand and their consequences on sustainability are discussed, reflecting shortly on the historical perspective of biomass use. Subsequently, Section 3 reflects on proposed strategies to mitigate these consequences, focusing on residual biomass. One important aspect of residual biomass use, called resource use change, is highlighted in Section 4. Section 5 discusses how different applications of residual biomass are related to sustainability. Reflecting on currently handled sustainability criteria the paper finally elaborates on conditions for the sustainable use of residual biomass.

2. Biomass supply and demand in the past and present: consequences for sustainability

Before the Industrial Revolution, biomass-based energy and other renewable energy sources dominated energy supplies (Meredith, 2013; Stern & Kander, 2012; Wrigley, 2013). These were mostly replaced by fossil energy carriers during and after the Industrial Revolution in Europe, initially dominated by burning coal instead of wood (Wrigley, 2013). Biomass applications as materials have undergone similar developments around a century later. Chemical research was initially driven by the potential to convert biomass into fuels and chemical products, and until the beginning of the 20th century many chemical materials were based on biomass. Petroleum-based products later gradually displaced most of these biomass-based products with the rise of the petrochemical industry in the 1950s (Pawelzik et al., 2013; Ragauskas et al., 2006; van Wyk, 2001; Veraart, van Hooff, Lambert, Lintsen, & Schippers, 2011).

For various reasons, efforts are currently being made to reduce or even abandon our consumption of fossil resources. These developments have stimulated the expansion of applications and modern technologies for biomass use. Contemporary applications accompany traditional biomass uses and include both new sources of energy and

materials, for example biofuels and bioplastics. The new opportunities to replace fossil resources with biomass have contributed to the vision of the so-called bioeconomy. Where in the past biomass inputs for non-food applications were gradually exchanged for fossil resources, it is now attempted to reverse this development. The bioeconomy is thus in fact a *renaissance* of biomass use.

However, achieving a switch back to biomass-based production brings with it a fundamental problem. Before the Industrial Revolution, biomass enabled, but also constrained economic growth: the available energy was limited to the annual regrowth (Wrigley, 2013). Before this limitation was overcome by the use of fossil resources, various countries around the world had already experienced shortages of biomass supply to fulfil their growing demands for energy (Reijnders, 2006). Overexploitation of resources created problems and triggered the switch to the use of fossil resources. In Britain, fossil material use soon exceeded what could have been supplied by sustainable biomass exploitation from woods, pastures or cropland (*ibid.*). Today, our energy demands are higher than ever and still predicted to rise. The fact that biomass resources could not supply sufficient sustainable energy before the Industrial Revolution provides an daunting perspective on current efforts to engage in a transition *back* to an economy driven by biomass. Paradoxically, the availability of fossil resources seemed practically unlimited during the Industrial Revolution, in contrast to "fresh" biomass, though fresh biomass regrows fast in comparison with virtually non-renewable fossil resources. Today we face the finite nature of fossil resources and the negative impacts of their exploitation and turn back to renewable, fresh biomass.

If renewable resources are to supply enough commodities to replace human consumption of fossil-based goods, this will have serious consequences for the demand for raw materials (van Dam, de Klerk-Engels, Struik, & Rabbinge, 2005). Improved agricultural techniques, modern processing technologies, and more efficient resource use may help to tackle this problem. However, land availability is considered a limiting factor for biomass supply for a bioeconomy (Alvarenga, Dewulf, & Van Langenhove, 2013; Brehmer, Struik, & Sanders, 2008; De Meester, Callewaert, De Mol, Van Langenhove, & Dewulf, 2011; Østergård, Markussen, & Jensen, 2010; Paula & Birrer, 2006). Global population growth and higher per capita consumption create a double rising pressure on raw materials and natural resources. Even with modern technologies and highly increased efficiency, the question remains whether humankind can fulfil its demands for resources in a sustainable way.

Rising demands for biomass resources can lead to undesired consequences. If the demands for material and energy applications were to be met with cultivated biomass while at the same time producing more food for a growing and increasingly prosperous world population, agricultural production would have to increase strongly. This would require either increased yields on the same area of land currently used for agricultural production, or an expansion of cultivated land.

A proposed alternative for biomass production is the cultivation of aquatic biomass, mainly algae, making use of the vast areas of the globe covered with water, thus avoiding competition for land areas. Cultivation and processing techniques have been under development for years and are currently further advanced, aiming for example at the production of biofuels (Bharathiraja et al., 2015; Chen, Zhou, Luo, Zhang, &

Chen, 2015; Trivedi, Aila, Bangwal, Kaul, & Garg, 2015). Nevertheless, use of land-based biomass resources is currently dominant and therefore chosen as focus in this paper.

Criticism of biofuels, and bioenergy in general, often refers to their effectiveness in reducing GHG emissions relative to fossil fuels. Proponents of bioenergy argue that the carbon uptake by plants makes biomass a carbon neutral resource, in contrast to fossil resources. Use of biomass for energy requires several processing steps consuming energy and materials, but the total sum is argued to be favourable in comparison with fossil fuels, due to the initial carbon uptake. However, changes in land use or expansion of land use can cause emissions of carbon that counteract the benefit of carbon uptake by plants. In 2008, Searchinger et al. published a study analysing the effects of direct and indirect land use changes on the overall GHG emissions of biofuel production in the USA. Since then, land use change (LUC), and especially indirect land use change (iLUC), dominate debates on the carbon footprint of bioenergy. Land use change can be defined as any change of one type of land use to another (Wicke, Verweij, van Meijl, van Vuuren, & Faaij, 2012). Biomass production can cause GHG emissions through land use change directly or indirectly. Direct LUC causes emissions if land harbouring carbon-rich ecosystems such as forests is converted specifically for the purpose of biomass production on that same land. GHG emissions from iLUC occur if land formerly used for the production of other feedstock (e.g. food production) is used for the production of biomass for energy or materials instead. As a consequence, carbon-rich land elsewhere is converted to make up for the feedstock no longer grown on the original land (Koh & Ghazoul, 2008; Plevin, O'Hare, Jones, Torn, & Gibbs, 2010; Searchinger et al., 2008; Wicke et al., 2012).

Both types of land use change can cause significant GHG emissions during and following the initial land use conversion. GHGs are emitted rapidly through slash and burn of natural land cover and microbial decomposition of plants, and over a prolonged period of time through the decay of roots (Fargione, Hill, Tilman, Polasky, & Hawthorne, 2008). In many cases the time before the initial emissions of carbon are offset by carbon savings of biofuels (carbon payback time) is long (Fargione et al., 2008; Gibbs et al., 2008; Lamers & Junginger, 2013), which is problematic for the mitigation of climate change in the short term.

Land use change furthermore has adverse effects additional to GHG emissions. The conversion of pristine ecosystems such as forests and grasslands, but also of diverse agroforestry systems, causes habitat destruction and may lead to biodiversity losses (Centi, Lanzafame, & Perathoner, 2011; Fargione et al., 2008; Koh & Ghazoul, 2008). While land use change effects have mostly been described for biofuels, they are also reflected in the scientific debate regarding the broader bioeconomy. Competition for land, competition for resources, and the uncertainty of emission reductions are the three most described problems regarding the contribution of a bioeconomy to sustainability (Pfau et al., 2014).

In summary, land use changes as a consequence of the renaissance of biomass for the production of materials and energy can lead to negative effects on carbon emissions, biodiversity, and food production, which counteract the sustainability objective of a bioeconomy.

3. Advantages and disadvantages of residual biomass use

To avoid the negative effects associated with land use change two strategies are often suggested: the use of degraded or marginal land for the production of biomass, and the use of residual biomass for the production of energy and materials (e.g. Fargione et al., 2008; Hatti-Kaul, 2010; Jenkins, 2008; Keijsers, Yılmaz, & van Dam, 2013; Lamers & Junginger, 2013; Landeweerd, Surette, & van Driel, 2011; Plevin et al., 2010; van Dam et al., 2005; Voll & Marquardt, 2012). While the advantages and disadvantages of marginal land in comparison to productive land have been discussed by some (e.g. Lamers & Junginger, 2013; Raghu, Spencer, Davis, & Wiedenmann, 2011; Vanholme et al., 2013), not much is known about the relationship between residual biomass and sustainability. Therefore this paper focuses on the strategy of using residual biomass.

Generally, two types of biomass resources for contemporary applications can be distinguished: cultivated biomass and residual biomass (see Figure 1). While Hoogwijk (2004) distinguishes between energy crops and biomass residues, the term “cultivated biomass” is chosen here to include all biomass produced specifically for non-food purposes. Next to energy crops, this includes for example biomass produced in forests or cultivated algae. Residual biomass is biomass that not produced for its use as for example energy source directly, but is a waste product of other processes. It is also referred to as "biomass residues" or "waste biomass". Hoogwijk (2004) distinguishes four types of residual biomass resources: agricultural residues, forest residues (incl. material processing residues), animal manure and organic wastes (e.g. waste wood of municipal solid waste). Here, the term “landscape residues” instead of forest residues is chosen to include biomass released during landscape maintenance activities in various types of landscapes. Next to forests, this includes half-natural landscapes influenced by humans, for example pastures or floodplains, but also roadside vegetation (see Figure 1).

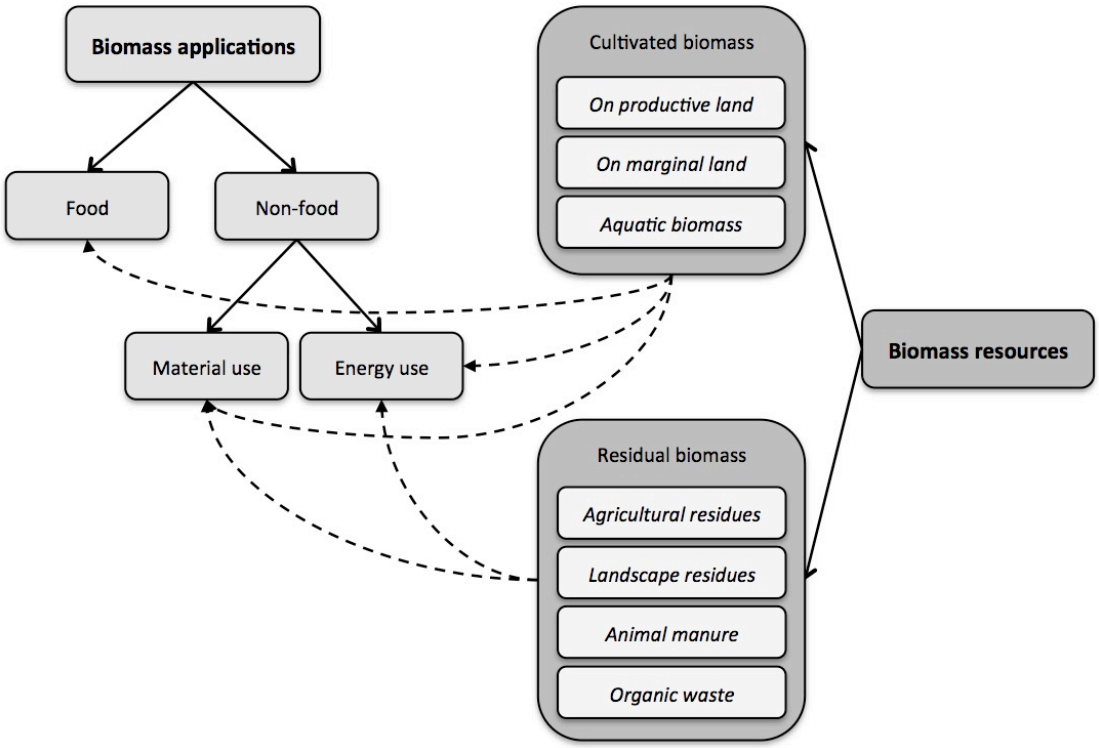

Figure 1: Contemporary biomass applications and resources

Using residual biomass as input for new production chains offers several sustainability advantages (Table 1). First, no additional land is required to produce biomass, which foregoes land use change. Second, applying otherwise unused material as input for new production chains reduces waste. Third, biomass that is left to rot may emit GHGs. Using this biomass will in the end still lead to GHG emissions, but by re-using this biomass other energy sources or materials can be substituted, reducing overall emissions. Finally, using residues increases the overall efficiency of resource use and can contribute to a "circular" resource use or a no-waste society, concepts closely related to sustainability.

However, residual biomass also poses a number of challenges (Table 1). Quantitative potentials of biomass supply from residual biomass are limited and much smaller than potentials from crops (Hoogwijk, 2004). It is therefore all the more important to use these streams in a sustainable way. It is questionable if potentials from residual biomass are high enough to fulfil demands in Europe, even in combination with biomass production on marginal land and increased efficiency.

Another challenge is the spatial availability and accessibility of residual biomass. Since the residues are by-products of other processes, they are initially situated in different, possibly widespread or difficult to reach locations. While cultivation of biomass is optimized for harvest and preservation of desired qualities, residues are not necessarily collected and stored appropriately. Collection and transportation for further use result in costs and emissions. Furthermore, processing, external impact, storage and transport can all lead to quality losses. These effects strongly influence the efficiency and sustainability of using residual biomass for applications within the bioeconomy. Ideally, processes would have to be optimized for reuse of waste streams by, for example, collecting residues on site and storing them appropriately or directly processing them further. Essentially, residues should then be treated as by-

products or secondary products instead of waste. It could be advantageous to adapt technologies to be efficient on a small scale to avoid long distance transport and storage, which is associated with problems of odours and volatile organic compounds (Centi et al., 2011).

The quality and characteristics of residual biomass pose an additional challenge. Coming from a variety of sources, residues are far more heterogenic than cultivated biomass sources, especially waste streams like organic waste in urban areas (Keijsers et al., 2013). Many studies argue that to achieve an efficient use of resources all components of any biomass resource should be used (Binder, Cefali, Blank, & Raines, 2010; Bramsiepe et al., 2012; Charlton, Elias, Fish, Fowler, & Gallagher, 2009; de Jong, Higson, Walsh, & Wellisch, 2012; De Meester et al., 2011; FitzPatrick, Champagne, Cunningham, & Whitney, 2010; Galvez et al., 2012; Hatti-Kaul, 2010; Pfau et al., 2014; Vanholme et al., 2013). This may refer to the use of all parts of crops, including parts that would otherwise be residues, or to specific components of plants, such as sugars, cellulose, or lignin. To use residual biomass resources efficiently, technology has to be adapted to cope with the variety and heterogeneity of different types of biomass and with all the different components.

Carbon payback times of substituting fossil resources with residual biomass differ between regional circumstances. Lamers & Junginger (2013) compared three different scenarios of substituting different fossil energy carriers with forest residues, showing that carbon payback times differ between 0 and 44 years. Thus, while some options offer almost immediate carbon benefits, the mitigation potential is not only determined by the feedstock and not all applications of residual biomass are equally successful. Case specific assessment is thus of great importance.

Finally, novel applications may disrupt existing functions of residual biomass. This aspect is rarely addressed when new applications of residual biomass are considered. Therefore the next Section elaborates on this challenge of a change in resource use.

Table 1: Expected advantages and challenges of residual biomass use.

Expected sustainability advantages	**Challenges**
No additional land required	Availability and accessibility
Waste reduction	Quality and components
GHG emission reduction	Carbon payback times dependent on regional circumstances
Circular resource use	Impact of resource use change (RUC)

4. Resource use change

When residual biomass is considered as waste, using it for a new purpose may appear to offer only advantages. However, even though residual biomass is not produced directly for a specific application, in many cases it does fulfil a function nonetheless.

Residues are seldom unused waste streams and even abandoned or treated waste can provide functions. If these resources are then used for new applications, this has consequences on the former function. I refer to this phenomenon as resource use change (RUC) in this paper, to demonstrate the resemblance with LUC. Where (i)LUC represents a change to current land use, RUC refers to new uses of resources that are provided by this current land use. These changes may or may not lead to LUC in consequence.

Table 2 shows several functions of residual biomass in different situations, illustrating them with examples, and referring to possible consequences of a RUC. Three current situations are distinguished. First, residual biomass can be extracted to serve as input in other supply chains. Second, biomass that is left behind – for example in the field or in an ecosystem – often fulfils a function. It may serve to sustain soil quality or provide ecosystem services. Soil organic matter is an important factor in both ecosystems and agricultural production. Biomass left behind is decomposed and provides important nutrients for renewed growth (Bot & Benites, 2005; Schils, 2012). Both fine and coarse debris provide habitats for various species and are therefore important for ecosystem health and biodiversity (CBS, PBL, & Wageningen UR, 2014; Jagers op Akkerhuis, Moraal, Veerkamp, Bijlsma, & Wijdeven, 2006; Nordén, Ryberg, Götmark, & Olausson, 2004; Sullivan et al., 2011). Third, biomass that is not used and enters waste treatment can still fulfil a function. Biomass residues such as organic or green waste are often treated and provide compost or energy.

Table 2: Functions of residual biomass and consequences of RUC.

	Function	Examples	Possible consequence RUC
Extraction	Input supply chains	• Wood residues for pallets • Wood residues for composite materials • Straw for fodder	• Disturbance of supply chains • Increase of market prices • Replacement with cultivated biomass
Left behind	Sustaining soil quality	Agricultural residues or straw mixed in soil	Soil degradation
	Ecosystem services	• Provision of food, nutrients or habitats • Input for trophic interactions • Enabling biodiversity	• Loss of ecosystem services • Disturbance of ecosystem functioning • Biodiversity loss
Waste treatment	Provision of energy	Energy from waste incineration	Reduced energy provision; increased use of fossil energy
	Provision of compost	Compost for soil organic matter re-nourishment	Reduced availability of compost; increased use of fossil fertilizers

Novel applications of residual biomass result in RUC because they alter the current situation. RUC may have undesired consequences. Similar to LUC, these can occur either directly or indirectly. Direct consequences are the losses of the current functions, as shown in Table 2. This can result in disturbed supply chains, degraded agricultural soils, disturbance of ecosystems or loss of ecosystem services. Indirect consequences do not influence the biomass function directly but occur due to the replacement of a current function. For example, if residues used as animal fodder are

devoted to new applications, the fodder has to be replaced with other sources, which may in turn lead to displacement effects such as iLUC (Asveld, van Est, & Stemerding, 2011; Tonini, Hamelin, & Astrup, 2014). If residues are used with the goal to avoid iLUC, as it is often argued, some applications may thus indirectly have the opposite effect.

Although RUC of residual biomass may have undesired consequences, it is worth considering. In some cases additional value may be achieved in combination with retaining the current function, while in others novel applications may achieve higher benefits than the current use. Especially low quality and waste streams may benefit from new processing. Biogenic waste that is currently incinerated may for example yield more energy through modern biogas installations. Other residues can be used first to produce energy or materials and subsequently extract nutrients for soil re-nourishment. In some cases, a compromise between current and new functions may be established, for example by applying mosaic landscape management allowing for different functions in different locations (Sullivan et al., 2011).

These examples show that residual biomass use for modern bioenergy or bio-based material production can be worthwhile. In some cases, it can achieve its promise as sustainable alternative to cultivated biomass, thereby avoiding land use change and negative consequences related to it. However, the above-described challenges show that this strategy is not a silver bullet. It requires case-specific evaluation, determining the potentials and consequences of a changed resource use.

5. Biomass applications and sustainability issues

Next to the RUC impact, the overall contribution of biomass use to sustainability is also determined by the aspired application itself. This Section discusses the relation between applications of residual biomass and sustainability.

Efficiency of resource use is an often-discussed aspect regarding biomass applications. Generally, more efficient use of resources is associated with greater sustainability (cf. Pfau et al., 2014). There are different views on what efficiency entails. While some argue that all components and by-products of any given biomass resource should be used, including the re-use or recycling of waste streams, others refer to choosing the best application for each quantity of resource (*ibid*). Different concepts address the optimization of biomass applications, for example cascading principles, biorefinery concepts or prioritization according to the value of the end product. They consider various applications, either prioritizing between them, or aiming at producing multiple products. All three concepts generally favour the production of (higher value) bio-based materials. For energy production, mainly lower value or otherwise unusable residues or by-products are considered. Through re-use of by-products and waste streams, residual biomass has the potential to link up different sectors. One sector can use the residual streams of another, thus creating synergies. Residual biomass is then seen as another raw material flow, rather than a waste stream (Commissie Duurzaamheidsvraagstukken Biomassa, 2014).

Even though increased efficiency of resource use may be advantageous, it does not necessarily lead to increased sustainability. The determination of efficiency is dependent on the objective of the application. Biomass is used to achieve a variety of

different objectives, for example replacing fossil fuels, reducing GHG emissions, producing renewable energy, creating economic benefits or stimulating rural development (Pfau et al., 2014). However, not all goals are necessarily related to increased sustainability. Consequently, efficiency in reaching some of these objectives does not necessarily lead to increased sustainability. Different applications should be weighed against one another in order to define how residual biomass use can best achieve a contribution to sustainability. Sustainability is then not only a boundary condition for biomass use, but the actual main goal. Efficiency of biomass applications can then be measured in terms of reaching a more sustainable situation.

Potentials to contribute to sustainability not only lie with the reduction of GHG emissions, although that is one of the main drivers of the bioeconomy and an important sustainability goal. Another important sustainability challenge is the disturbance of global biogeochemical flows resulting, for example, from agricultural activities applying artificial fertilizers. Especially Phosphorus and Nitrogen distributions across the globe are dangerously disturbed, and biogeochemical flows have been identified as one of the planetary boundaries (Steffen et al., 2015). Recovery of minerals from biomass as an additional processing step offers the potential to reallocate minerals and replace artificial fertilizers, thereby counteracting this disturbance. Another chance lies with the production of environmentally friendly products. Although not all products that are bio-based are necessarily beneficial, new processes have the potential to create products that are for example less toxic or biodegradable, contributing to solving pollution problems.

6. Conditions for sustainable residual biomass use

The use of residual biomass as alternative for cultivated biomass offers several advantages, but it cannot be considered a silver bullet for a sustainable bioeconomy. Changing current use of resources, even if it means sourcing previously unused biomass residues, can have negative impacts outweighing the advantages. Whether residual biomass use contributes to sustainability depends on a variety of conditions, often influenced by regional differences. In this Section conditions for sustainable use of residual biomass are discussed, considering existing sustainability criteria and building on the previous sections.

One approach to set boundary conditions for sustainable use of biomass resources has been the development of sustainability criteria or standards. Such criteria mainly demand that biomass applications achieve GHG savings in comparison to their fossil-based alternatives, and that biomass is not produced on land with high biodiversity or high carbon stocks (Commissie Duurzaamheidsvraagstukken Biomassa, 2009; European Parliament, 2009). Regarding residual biomass a distinction is made between agricultural, aquacultural, fisheries and forestry residues on the one hand, and all other waste and residues on the other hand. Criteria for the latter group are less strict, essentially reduced to GHG emission reductions (European Parliament, 2009). Some argue to include a criterion ensuring that the extraction of residual biomass does not negatively influence soil quality (Commissie Duurzaamheidsvraagstukken Biomassa, 2009). Sustainability criteria are criticized for their restriction to certain bioenergy applications and the exclusion of impacts that are difficult to measure, such as iLUC (Asveld et al., 2011; Plevin et al., 2010). Universal application to all

resources and all applications as well as consideration of all effects would be beneficial to enable a level playing field.

The previous sections have shown that additional to the aspects addressed by current sustainability criteria it is crucial to consider the origin and current use or function of residual biomass. New applications always present a RUC. Both GHG emissions and influences on soil quality are valid concerns, but RUC can have additional environmental impacts such as biodiversity loss or iLUC, as well as influences on other supply chains currently using the residual biomass. To maximise the benefits, different potential applications, or combinations of applications, should be compared since they may contribute to sustainability in varying degrees. It has to be thoroughly investigated what the effects of RUC are, in comparison with the current use or function.

Table 3 presents a checklist that can be used by public or private actors considering the use of residual biomass to evaluate and compare the contribution to sustainability of different resource and application options. It is divided into three sections addressing the current use of residual biomass, the potential application, and the impact of RUC.

Table 3: Checklist for sustainable residual biomass use.

Topic	Relevance	Checkpoint
Current Use	Residual biomass may already be in use for another application or fulfil a function when left behind. Examples: Wood residues are used for the production of composite materials and landscape residues may fulfil ecosystem services when left behind, e.g. maintaining soil quality or offering habitats.	Is the biomass currently being used or does it fulfil any function?
		Do the residues currently fulfil ecosystem services when left behind?
		Can the current use be replaced sustainably?
Potential Application	Depending on sustainability goals, residual biomass can be used for a variety of applications. The measure of efficiency depends on these goals. If residual biomass is to contribute to sustainability, several aspects should be considered to weigh different application options. Furthermore, applications should be adapted to use residual biomass optimally.	Does the envisaged application contribute to sustainability efficiently? Consider the following aspects: • Reduction of GHG emissions • Replacement of fossil resources • Mitigation of disturbance of biogeochemical flows (e.g. N, P recovery) • Production of environmentally friendly products (e.g. non-toxic, biodegradable)
		Are technologies, organization and logistics adapted to use residual biomass optimally?
		Are synergies between biomass processing sectors optimized?
Impact of RUC	Changing current use may cause negative impacts. Current supply chains may be disrupted, causing a switch to other resources and (i)LUC. Removing biomass from ecosystems can have negative impacts on the provision of ecosystem services.	Are ecosystem services reduced or lost as a consequence of RUC?
		Are current supply chains interrupted?
		Does the RUC cause (i)LUC?
		Is the transition cost and energy efficient?
		Do the benefits of new applications outweigh the negative impacts of RUC?

To determine the potential impacts of RUC, current uses and functions have to be identified and valued. The consequences of loss or modification of these uses must be determined, considering possible sustainable alternatives. Next, different applications must be weighed, comparing their contributions to sustainability and determining the most beneficial application. They should be valued according to their potential to reduce GHG emissions, replace fossil resources, mitigate disturbance of biogeochemical flows and produce environmentally friendly products. Applications must be adapted to the specifics of residual biomass to maximize the resource efficiency. As discussed in Section 3, residual biomass can be difficult to access and of lower quality than cultivated biomass. Technologies and logistics should be adapted to minimize these disadvantages so that residual biomass can effectively replace fossil resources. Biomass processing in all relevant sectors should be adapted to enable optimal use of residual biomass and waste or by-products arising during processing. Striving for an efficient use of residues and waste streams furthermore has the potential to create synergies between different biomass applications and sectors. What is considered waste in one sector may well serve as input for other uses.

Increased synergies provide great potential to increase sustainability in a bioeconomy and cope with competition for various applications. Efficient use of residual biomass links up well with sustainability concepts considering the reuse of waste as resources (e.g. circular economy, cradle to cradle). Finally, the impacts of the RUC have to be determined.

How benefits and costs of RUC are valued largely depends on the sustainability goals of the envisaged biomass application. The comparison should not be based solely on monetary terms. Current sustainability criteria only require a GHG emission reduction for certain residual biomass resources and are restricted to liquid bioenergy applications. However, RUC of all types of residues can have additional impacts that should be evaluated. The GHG emission impact and the potential to replace fossil resources are quantifiable, but impacts on soil fertility, iLUC, and ecosystem services such as habitats and biodiversity are more difficult to value. Their consideration is, however, important to estimate all costs.

7. Conclusion

The transition to a bioeconomy can offer important steps towards a more sustainable situation, like the reduction of the unsustainable exploitation of fossil resources, reduction of GHG emissions, and the provision of more environmentally friendly products. However, if land use changes are required to produce biomass, negative impacts often outweigh the benefits. Production on marginal land and the use of residual biomass are often proposed as strategies for sustainable biomass supply. But the assumption that residual biomass use is always sustainable because it does not cause (i)LUC is inappropriate; it is not a silver bullet to ensure a sustainable bioeconomy.

When it comes to cultivated biomass, competition for land, (i)LUC and carbon payback times are some of the main concerns which should be addressed through sustainability criteria. Residual biomass is a different type of resource and requires different considerations. It is false to generalize that residues are waste streams that are currently unused, assuming their exploitation is always beneficial and applying less strict sustainability criteria. RUC to realize new applications always has consequences, whether the resource is currently used, left behind or enters waste treatment. Therefore, the sustainability of new applications has to be evaluated based on the effects of the RUC.

It is recommended that public and private parties considering the use of residual biomass include all potential impacts of RUC in the evaluation of new applications. These potential impacts furthermore show the complexity of interactions between different supply and demand systems for biomass. Choices between resources and applications should be weighed based on their contribution to sustainability in order to reach the objectives of a bioeconomy. Reliable methods to assess impacts that are difficult to quantify at the moment, such as iLUC or biodiversity, should be developed. Facing a great demand for biomass all resources that can be supplied sustainably are helpful. Residual biomass should not be considered waste but a potential resource, applying above-discussed conditions to ensure that it contributes to a sustainable bioeconomy.

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