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Assessing the Availability of Terrestrial Biotic Materials in Product Systems (BIRD)

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Abstract: Availability of abiotic resources has been a topic of concern in recent years, resulting in several approaches being published to determine their availability on country and product level. However, the availability of biotic materials has not been analyzed to this extent yet. Therefore, an approach to determine possible limitations to availability of terrestrial biotic materials over the entire supply chain is introduced. The approach considers 24 categories overall as well as associated category indicators for the five dimensions: physical, socio-economic, abiotic, social and environmental constraints. This ensures a comprehensive availability assessment of bio-based product systems. The approach is applied to a case study comparing biodiesel produced from rapeseed and soy beans. The study shows that the determination of indicator values is feasible for most categories and their interpretation leads to meaningful conclusions. Thus, the approach leads to a more comprehensive assessment of availability aspects and supports better informed decision making in industry and policy.

Keywords: biotic materials; resource availability; socio-economic availability; life cycle assessment; supply risk

1. Introduction

The availability of abiotic resources has been a topic of discussion recently, leading to several approaches being published to determine their availability on country and product level (e.g., [1–7]). However, the availability of biotic materials has not been analyzed to this extent yet.

First, a distinction has to be made regarding biotic resources and man-made biotic materials (see Figure 1). Biotic resources are defined as living objects (species) such as wild fish or trees removed from the natural environment by human activities, whereas man-made biotic materials refer to species extracted from the technosphere [8,9]. The term "biotic materials" includes both biotic resources and man-made biotic materials. Biotic materials are classified as renewable as they can regenerate within human lifetime.

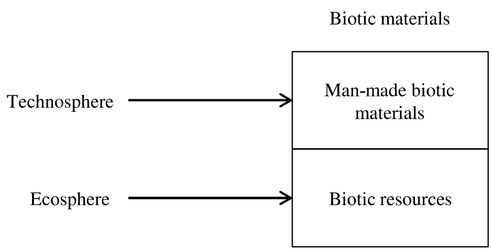


Figure 1. Overview of the terms man-made biotic materials, biotic resources and biotic materials.

Having materials available at any time is a precondition for economic development as companies rely on certain materials to produce goods and services [10–12]. Limitations to availability can restrict productivity and (in the worst case) might lead to production stops. Such a scenario would result in severe damage to the company as well as to the affected regions and countries. In addition to job losses further aspects like healthcare system for the employees might be affected. Therefore, ultimately the whole society is impacted when a company stops production due to availability restrictions of materials [13–16].

Availability of biotic resources has been a topic of concern for several years, especially in relation to such topics as overfishing, elephants being killed for ivory as well as deforestation of rain forest [17]. Fish consumption plays a vital role for the livelihood of many people as over two billion people rely on fish as an important part of their daily diet [18,19] and the rainforest is one of the biggest hotspots for biodiversity and billions of people depend on the services it supplies (e.g., food and shelter). The hunt for ivory has led to the decrease of African elephant population to the point where they are almost extinct [20,21]. Considering recent rises in fish yields and increasing shares of the rainforest being transformed into agricultural areas the pressure on these resources is steadily intensifying. For the assessment of biotic resource use of products, the Life Cycle Assessment (LCA) methodology according to ISO 14040/44 is commonly used. Several Life Cycle Impact Assessment (LCIA) methods exist to determine depletion of biotic resource (e.g., of fish [22–24] or loss of biodiversity in relation to deforestation of rain forest areas e.g., [11,25,26]).

Man-made biotic materials are restricted in their availability for industrial processes. However, these restrictions somewhat differ compared to the constraints of abiotic resources. So far no method exists for the assessment of man-made biotic materials extracted from the technosphere, e.g., agricultural products such as maize, rapeseed or timber from cultivated forests (silviculture). The availability of these materials has so far not been considered in LCA, even though their accessibility can be restricted as well. For example, predicted high demand of cellulosic fibers (from cotton) in the coming years [27] might lead to the restriction of the overall availability of cotton as a consequence.

Biotic materials are subject to various constraints which can influence their availability (as addressed by [1,28–32]). Most of these studies consider physical and socio-economic constraints of abiotic resources only, but do not include biotic materials in their approaches ([1,28,32]). Carrying out a bottom-up analysis, the compatibility of these categories and indicators for biotic materials was analyzed. With regard to socio-economic availability of biotic materials the approach considering the widest range of categories and indicators is the one of Fraunhofer (2013) [31], which takes the following categories into account: substitution, recycling, concentration of producing countries and poor governance as well as environmental performance of producing countries. Besides substitution all categories are also considered within the introduced (BIRD) approach as follows: For the category recycling, another indicator is applied than that proposed by Fraunhofer (2013) [31] because the recycled content was evaluated to be more adequate for the assessment of primary material availability. Indicators for the categories concentration and governance of producing countries are identical. Substitution is not included within the introduced approach as it is typically an aspect considered within vulnerability [3,5,6,32,33] and is challenging to determine on a material level. Additionally, the introduced approach provides indicators for seven more socio-economic constraints not considered by Fraunhofer (2013).

Furthermore, using a top-down procedure existing case studies of species used as biotic materials as well as bio-based products were reviewed, which address individual aspects related to the availability of agricultural and silvi-cultural products (e.g., land and phosphorus use [29,30]). Thus, based on the applied Top-down-Bottom-up procedure the following aspects are identified as being relevant for the availability of biotic materials:

- physical constraints
- socio-economic constraints
- abiotic constraints

- social constraints and
- environmental constraints

The introduced approach to determine the availability of terrestrial biotic materials in product systems (BIRD) proposes several categories and indicators to quantify these aspects and, therefore, represents the first assessment framework to comprehensively evaluate the availability of biotic materials. Its aim is to provide a methodology to adequately assess potential restrictions to availability of biotic materials for product systems.

2. BIRD Method

BIRD focuses on terrestrial biotic materials because, firstly, most biotic materials for human consumption except fish are produced from terrestrial materials and, secondly, the availability of aquatic materials is influenced by other aspects (e.g., ocean acidification [34]) and thus should be assessed separately [35]. The aim of the introduced approach is to evaluate possible restrictions to availability of terrestrial biotic materials (in the following terrestrial biotic materials are referred to as biotic materials) along the supply chain. Based on recent publications regarding the availability of abiotic materials (e.g., [1,28,32]) as well as additional aspects of biotic material availability (e.g., Food First Principle [36]) a Top-down-Bottom-up approach (established and already applied for the assessment of abiotic resource availability by Bach et al. (2016) [28]) is applied. Dimensions and categories influencing the availability of biotic materials are identified with regard to supply chain stages where these limitations occur (see Figure 2). Overall the five dimensions physical, socio-economic, abiotic, social and environmental constraints are considered. Physical constraints refer to limited availability of species used as biotic materials and are quantified for the categories biotic resource depletion, replenishment rate and anthropogenic availability. Socio economic constraints decrease the access to biotic materials. Following categories with regard to socio-economic constraints are considered within BIRD: concentration of resources, of harvesting and company concentration, demand growth, political instability, trade barriers, price fluctuations, occurrence as co-product, storage complexity as well as recycling. Phosphorus, land and water availability as well as natural disasters can reduce the occurrence of species used as biotic materials and are assessed within the dimension abiotic constraints. Social constraints refer to limited availability of biotic materials due to challenges regarding compliance with social and environmental standards as well as food security. Possible limitations in availability can occur due to the environmental constraints climate change, acidification, eutrophication, ozone depletion and smog.

The supply chain of products produced from biotic materials can be divided into the following stages: nature, cultivation and harvesting of terrestrial species used as resources/materials, processing of materials (where an intermediate product is the output) and production of several (additional intermediate) products depending on the considered product system (e.g., the final product rapeseed oil has less supply chain stages than the final product biofuel, which is made out of vegetable oils like rapeseed oil). Whereas some categories are only valid for one specific supply chain stage (e.g., replenishment rate), other apply for several stages (e.g., demand growth). Some categories are predominately valid for one supply chain stage, but can—under special circumstances—also influence other supply chains stages, e.g., water availability (these are marked with a dotted grey line in Figure 2).

Most of the categories are valid for biotic resources as well as man-made biotic materials. Exceptions exist for the categories biotic resource depletion and concentration of resources, which are only valid for biotic resources and the categories phosphorus availability and food security, which are only valid for man-made biotic materials.

Furthermore, indicators for quantifying the categories are proposed. All indicators are constructed globally. Thus, possible restrictions to availability are determined as average limitation and do not consider individual regions.

The assessment of product systems is often carried out by LCA [37–39]. Thus, the approach introduced is designed to be implemented into LCA in the future, e.g., the defined categories of the introduced approach are similar to the categories in LCA and the proposed indicators can function as category indicators. In the following the identified dimensions and categories as well as related indicators are introduced in more detail. The approach is further tested in a case study (see Section 3) to analyze applicability and discuss robustness of results.

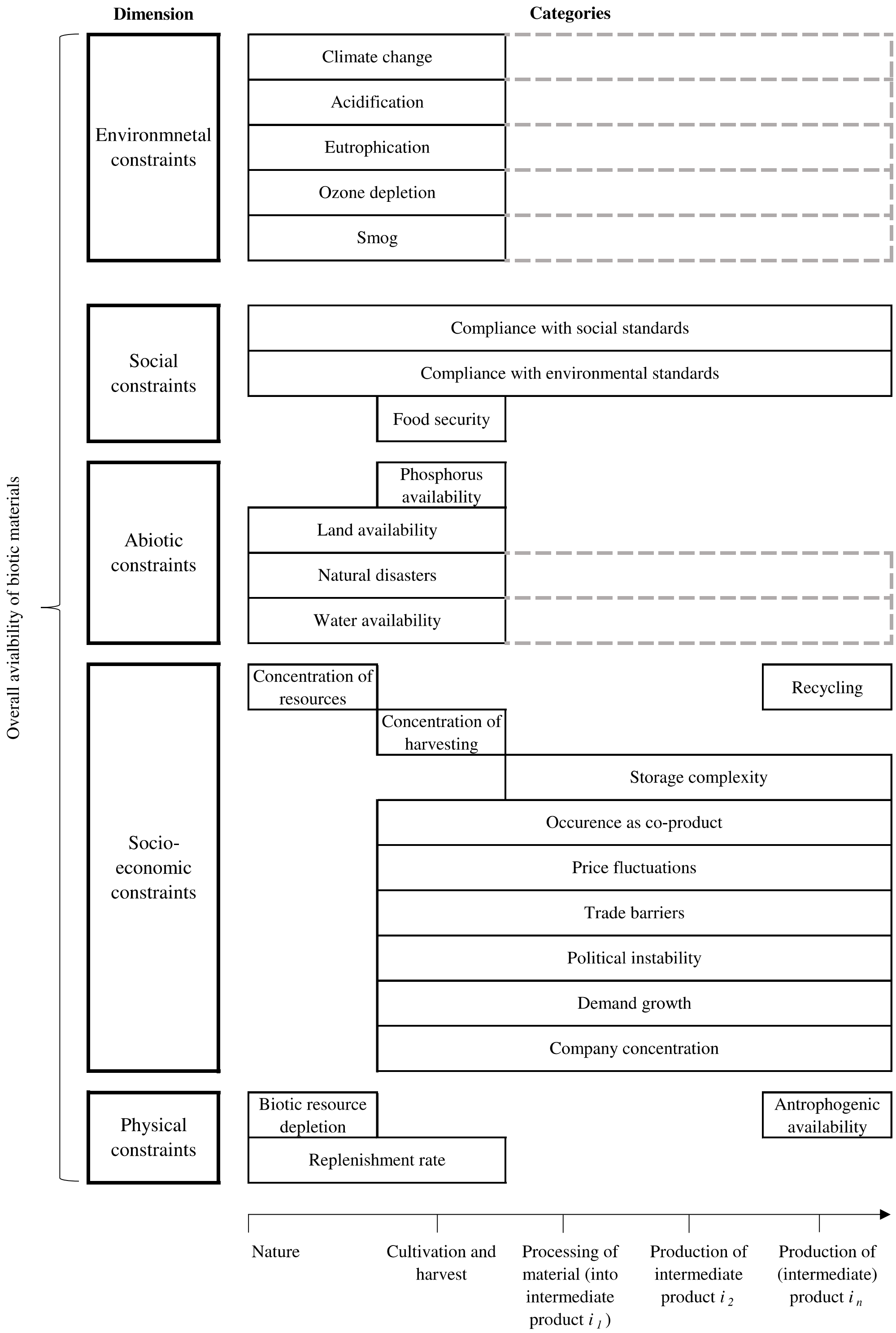


Figure 2. Overview of identified dimensions and categories influencing the availability of biotic materials and (intermediate) products as well as the related stages of the supply chain.

2.1. Physical Constraints

Physical constraints refer to availability restrictions due to limited existence of biotic resources and materials in the ecosphere (environment) and/or technosphere. These restrictions are influenced by existing stocks, extraction rate, replenishment rate and anthropogenic availability (see Figure 3).

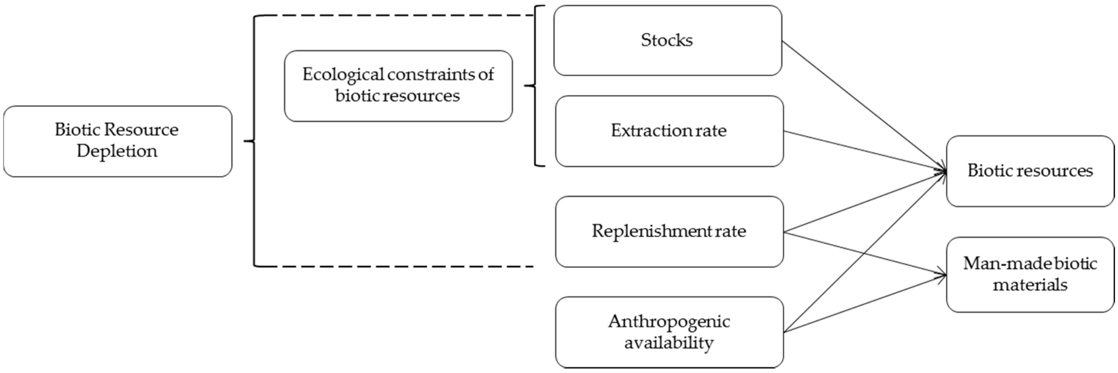


Figure 3. Overview of physical constraints influencing biotic resources and man-made biotic materials.

2.1.1. Biotic Resources

Availability of biotic resources decreases when the amount of resources extracted from the environment exceeds the replenishment rate and therefore decreases the resource stock (biotic resource depletion) [8]. Some basic concepts to measure biotic resource depletion exist modelled in line with the Abiotic Resource Depletion indicator [40,41], by Heijungs et al. (1992) [42] and Sas (1997) [43]. However, these frameworks have never reached a mature level to be applicable in case studies because biotic resource depletion has seldom been considered in LCA. Only very specific products (e.g., exotic animal leather, ivory, rare timber and medical plants) consist of biotic resources.

Based on these studies the Biotic Resource Availability (BRA) indicator according to Equation (1) is proposed as the first approach to determine resource depletion within the BIRD method.

$$\mathrm{BRA_i} = \frac{\mathrm{BRAI_i}}{\mathrm{BRAI_{reference}}} = \frac{\left[\frac{\text{extraction rate}_i - \text{replenishment rate}_i}{(\text{resource stocks}_i)^2}\right] \times \mathrm{TSI_i}}{\mathrm{BRAI_{reference}}} \quad (1)$$

The Biotic Resource Availability Indicator (BRAI) of a species i is set in relation to the BRAI of a reference species. The BRAI is determined by subtracting the replenishment rate from the extraction rate and dividing it by the squared resource stock. The resource stock is squared as the BRA method is based on the Abiotic Resource Depletion Potential approach [40,41]. The higher the extraction rate is the more species are extracted. If the extraction rate is higher than the replenishment rate, existing stocks are depleted. However, as the calculated value is only a snapshot of the current situation and does not reflect the depletion in the last years, the Threatened Species Index (TSI) is considered in addition. Depletion of endangered species is worse as depletion of less or one endangered species. The TSI is based on the evaluation of the rating system of the International Union for Conservation of Nature and Natural Resources (IUCN) Red List of Threatened Species, which is divided into six classes [20,44]. These qualitative classes are translated into quantitative values according to Table 1. For a species of least concern the quantitative value is set to 1, thus, the TSI does not influence the BRAI result. For a critically endangered species the TSI value is set to 100. This way, the BRAI is influenced by the TSI, but not exclusively. To determine the values for the other classes there are divided into 3 categories with the same range (25).

Table 1. Classes of the International Union for Conservation of Nature and Natural Resources (IUCN) (2016) [20] Red List of Threatened Species and translated quantitative Threatened Species Index (TSI) values.

Classes of IUCN Red List of Threatened Species	TSI Value
Least concern	1
Near threatened	25
Vulnerable	50
Endangered	75
Critically endangered	100

To compare the availability of different biotic resources the calculated value is set in relation to the reference species African elephant (this is the same approach as for the Abiotic Resource Depletion indicator [40], which uses antimony as a reference). The African elephant, which is hunted for its ivory, is classified as vulnerable. It is chosen as the reference species because data are easily available (calculations of the BRAI for African elephant are shown in the supplementary material—Section 1). A high BRA refers to high possible restrictions to availability of the considered resource, whereas a smaller BRA relates to lower possible restrictions to availability.

2.1.2. Man-Made Biotic Materials

For man-made biotic materials existing stocks as well as extraction rates are not limiting factors. These materials do not occur naturally and therefore do not have a stock. Furthermore, they are harvested to be cultivated (extraction rate is predefined). Not extracting man-made biotic materials would not automatically lead to an accumulation of these materials as they will be deteriorating in a certain time frame. The replenishment rate (growth period and/or the amount of yield), however, influences the availability of man-made biotic materials as it determines how often and to what extend a species used as a material is replenished. Species with high growth rates can replenish within a short time frame, for example maize, which can be harvested after half a year. Thus, the availability is higher than for species with average (e.g., bamboo, which must grow three years before being harvested) or low growth rates (e.g., shea or walnut trees with an initial growth time of 10 years before the first harvest).

For the assessment of the influence of the replenishment rate on availability within the BIRD method the following approach is introduced (see Figure 4).

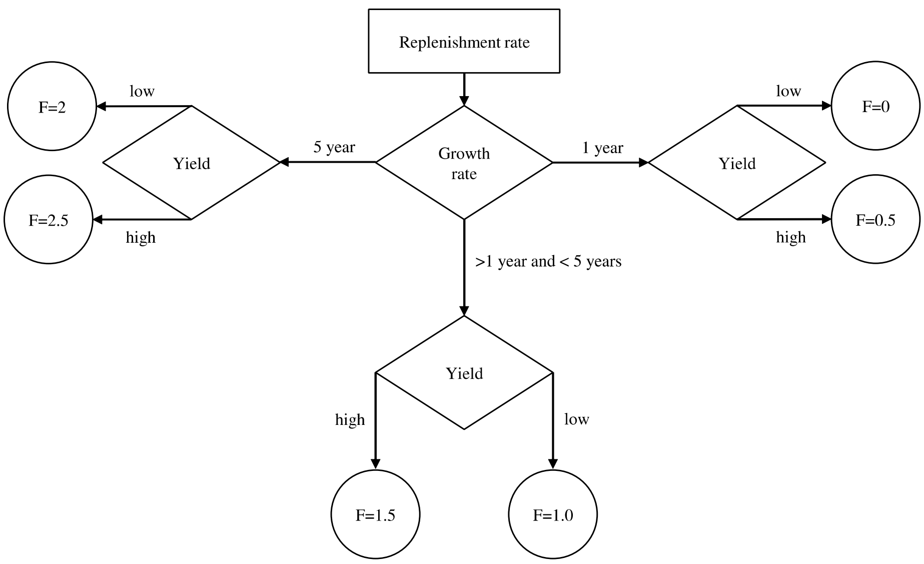


Figure 4. Decision tree to determine the replenishment rate of man-made biotic materials.

The growth rate is divided into three groups: growth rate less than one year, growth rate beyond 1 year but less than 5 years and growth rate beyond 5 years. These groups are determined on the basis that a growth rate below one year is not critical because the species used as a biotic material can be regenerated within a short time frame. A growth rate beyond 5 years is critical as during this time frame (or even longer) no species can be harvested for human purposes. Furthermore, the overall yield of a species influences the availability of a biotic material. In case of a low yield only a small amount of this specific species used as a biotic material is available. Is the yield high, the availability of a certain species is high as well. Thereby, only the average yield of the species is considered, no distinctions regarding different regions are made. However, such a distinction could be made when regionalized data is available. Determining which amount of yield can be considered as low or high is challenging and will not be fully answered within this article (an example on how to classify materials can be found in the case study—Section 3). Low indicator values refer to a high replenishment rate and thus fewer restrictions to availability whereas high indicator values refer to a low replenishment rate and therefore high possible restrictions to availability. The scenario with no (or the lowest) restrictions to availability is assigned the number zero, whereas the other scenarios are assigned a higher number depending on the increasing importance for restricting the availability. The numbers are chosen based on experiences from former work of the authors (e.g., ESSENZ [28], ESP [1]).

The annual yield is not considered to determine the replenishment rate (but for the socio-economic availability) as it does not allow conclusions regarding the overall replenishment capability. If a species is quantitative available is important for the current supply situations (thus considered within the socio-economic availability), but can change when the market structure changes. The replenishment rate of a species is independent of the market structure and only depends on the characteristics of the species.

2.1.3. Biotic Materials

Biotic resources as well as man-made biotic materials are transferred into the technosphere, where they can accumulate and thus, are available to be used further. Currently, there are no existing methods to measure the anthropogenic availability of biotic materials. In the BIRD method, the use of biotic materials is applied as a basis to determine the influence of anthropogenic stocks on the availability of biotic materials (see Table 2). Whether a biotic material enriches the anthropogenic stock depends on its original use. Materials, which are consumed (e.g., as food, feed or fuel) during their first use phase cannot be reused. Materials used for or in products stay in the technosphere and thus have the potential to be reused. However, their reuse depends further on the product design. If the product is almost completely made out of a biotic material like paper or wooden furniture, it is likely to be recycled. Products where the fiber of the biotic material is used together with several other materials like in bio polymers are harder to recycle and thus, are often incinerated after one use phase. However, because they are accumulated in the technosphere, they have the potential to enrich the anthropogenic stock when improved recycling technologies are available. The values for quantification were chosen based on the experiences of the authors obtained from former method development. However, as other indicator values within this approach rank from 0 to 1, a similar scale was preferred. To evaluate to what extent a biotic material contributes to the anthropogenic stock (ASR—anthropogenic stock restraint) the global production shares (sgp) of a material i are multiplied with the quantitative factor *F* and then summed up (see Equation (2)).

$$\mathrm{ASR_i} = \left(\mathrm{sgp_{i,F}} \times \mathrm{F_F}\right) + \left(\mathrm{sgp_{i,P1}} \times \mathrm{F_{P1}}\right) + \left(\mathrm{sgp_{i,P2}} \times \mathrm{F_{P2}}\right) \tag{2}$$

A high ASR refers to a low contribution to the anthropogenic stock, whereas a low ARA refers to a high contribution. This approach is used as no data is available on anthropogenic bio-based products.

Table 2. Classes related to use of the biotic material and translated quantifiable factors.

Classes Related to Use of Biotic Material	Quantitative Factor F
F: Food, feed and fuel	1
P1: Product, made from several materials	0.5
P2: Product, primarily made from biotic materials	0

2.2. Socio-Economic Constraints

The socio-economic availability of materials is influenced by structural conditions of the market as well as societal structures inhibiting the supply security. For example, the political instabilities of a country can lead to restraints in availability as e.g., corruption or revolutions disrupt the ability to effectively implement robust policies including ones related to material export, etc. So far several methods to determine the socio-economic availability of abiotic materials exist (e.g., [15,28,32]), which are not adapted for the application to biotic materials but can be used as a basis to determine socio-economic aspects influencing the availability of biotic materials. Within the method of the Association of German Engineers (Verein Deutscher Ingenieure—VDI) biotic materials are considered, but often only evaluated through expert judgment [45]. The study of (Fraunhofer 2013) [31] provides a first assessment methodology regarding the availability of biotic materials. Considered aspects are substitution, recycling capability, concentration of producing countries as well as political stability. Thus, the method by Fraunhofer (2013) [31] and (VDI 2013) [45] are used as a basis for the development of a comprehensive approach for the socio-economic availability of biotic materials. Furthermore, the ESSENZ method [28] developed by the authors is taken into account as it is a methodology to assess the resource efficiency including the socio-economic availability of abiotic resources for product systems.

In the following, the categories as well as associated indicators for quantifying these categories are introduced. Overall 10 potential economic constraints leading to possible supply shortages along the product's value chain are identified. For all categories high values are referring to high restrictions to availability and low values relate to low restrictions.

2.2.1. Concentration of Resources, Harvesting and Company Concentration

A high concentration of an activity (e.g., trading biotic materials) refers to the extent to which a relatively small number of companies or countries account for a large share of this activity (e.g., [32,46]). High concentrations increase potential restrictions to availability. In the introduced approach the concentration of resources, company concentration and concentration of harvesting are considered. The concentration can be measured by the Herfindahl-Hirschmann-Index (HHI) [47], which is calculated as the sum of the squared market shares (global production share (sgp)) (see Equation (3)) and ranks from 0 to 1.

$$\mathrm{HHI_i} = \sum \left(\mathrm{sgp_{i,x}}\right)^2 \quad (3)$$

By determining the concentration of resources, the number of countries where the considered species (resource) is available and can be extracted as well as their share in the global stocks are reflected. In case all species occur in only few countries, the concentration and as consequence risk of limited availability is high. This category only applies to species used as biotic resources and not to man-made biotic materials because only species used as biotic resources occur in nature.

Concentration of harvesting refers to the number of countries harvesting species used as biotic materials and the share of the globally produced material. Limited availability can occur when most of the harvesting activities occur in only few countries. This category applies to biotic resources as well as man-made biotic materials because for both species are harvested.

Company concentration reflects the number of companies trading and their share of the globally produced material. When only few companies market most of the materials, a high company concentration occurs, which can reduce the availability of resources. High company concentration can have an influence in every supply chain stage. This category is important for biotic resources as well as man-made biotic materials because the availability of both is influenced by companies trading them.

2.2.2. Political Instability

The risk of limited availability of biotic materials is higher for unstable countries, where political systems and legal procedures are not reliable. For example, potential uprisings and corruption might interrupt the cultivation and harvest of species used as biotic materials. Politically unstable countries can influence the availability of biotic materials over the whole supply chain. Next to cultivation and harvesting, also processing and production of (intermediate) products can take place in unstable countries. Political instability of countries can be a limiting factor for the availability of biotic resources as well as man-made biotic materials because both might be processed in instable countries. The quantification of the political instability (PIS) is based on the Worldwide Governance Indicators [48,49]. The indicators consider the key aspects voice and accountability, political stability and absence of violence, government effectiveness, regulatory quality, rule of law and control of corruption for over 210 countries. As all six indicators reflect fragments of an unbalanced system, they are combined to an aggregated evenly weighted index ($WGII_x$). To determine the political instability in relation to a biotic material i the material's global production (or consumption) share (sgp) per country x is multiplied with the $WGII_x$ and summed up (see Equation (4)). The global production shares are used as a basis to determine the country distribution of species used as biotic materials for the supply chain stages nature as well as cultivation and harvest. The global consumption shares are applied as a basis to determine the country distribution regarding the production of biotic materials (made out of species) for the supply chain stages processing of material (into intermediate product), production of intermediate product(s) and production of the final product. If the specific countries in which production occurs are known, these shares should be used instead of the generalized country distribution.

$$\mathrm{PIS_i} = \sum(\mathrm{sgp_{x,i}} \times \mathrm{WGII_x}) \tag{4}$$

2.2.3. Demand Growth

Demand describes the need for biotic materials. Demand growth occurs when the demand is increasing. When the demand is higher than the amount of materials currently obtained, possible restraints to availability can occur. Demand growth can occur in all supply chain stages because not only the demand of harvested materials but also of (intermediate) products can increase. It occurs for biotic resources as well as man-made biotic materials as both are used. If the demand for one specific (intermediate) product increases, the demand of harvested materials increases as well. Demand growth (DG) of raw materials is determined by calculating their production (or consumption) increase (or decrease) over the last five years (see Equation (5)).

$$\mathrm{DG_i} = \frac{\sum_1^5\left(\frac{\text{global production of year n} + 1}{\text{global production of year n}} - 1\right)}{4} \tag{5}$$

2.2.4. Trade Barriers

Barriers to trade regarding the export (e.g., export duty) of biotic materials can limit their availability. This might occur when biotic material producing countries reduce or terminate the export of specific materials or (intermediate) products. These trade barriers can occur in all stages of the supply chain since both harvested and processed materials or (intermediate) products can be subject to trade. Trade barriers apply to biotic resources as well as man-made biotic materials. To quantify the trade barriers (TB) the Enabling Trade Index (ETI) [50] is used. The ETI is established by the World Economic Forum and ranks countries regarding their policy for trading goods. To determine existing trade barriers in relation to a biotic material i the global production (or consumption) share (sgp) of the material i per country x is multiplied with the ETI and summed up (see Equation (6)).

$$TB_i = \sum \left(sgp_{x,i} \times ETI_x \right) \tag{6}$$

2.2.5. Price Fluctuation

Prices of biotic materials fluctuate depending on current market situations. Companies consider predictable price fluctuations in their raw material planning processes. However, when unexpected price fluctuations occur, compensation might not be possible and the availability of materials is restricted. Price fluctuation can occur in every supply chain stage for biotic materials as well as (intermediate) products because they are sold at the world market. Fluctuations can be quantified by the volatility indicator, e.g., [51].

However, often the necessary market data is not available to calculate the volatility of a biotic material. Thus, other indicators have to be applied, e.g., commodity price index by Barrientos and Soria (2016) [52].

2.2.6. Occurrence as Co-Product

Production processes are established to produce a specific main product (e.g., production of oil from rapeseed). Next to the main product co-products can be produced alongside (e.g., rapeseed cake). If the economic importance of the main product is decreasing and production is declining, the co-product is not produced further as well. This leads to limited availability of the co-product [53–55]. Occurrence as co-product can influence the availability over the whole supply chain and affects biotic resources as well as man-made biotic materials since both can occur as main and co-products. Qualitative information regarding occurrence of co-products can be transformed into quantitative values according to the scheme presented in Table 3. The values are assigned based on the ESSENZ approach [28]. One is set as the highest value and is divided into 3 same-range categories (as numbers for three other classes have to be assigned). The class only mined as main product is set to zero as restrictions to availability are not to be expected.

Table 3. Qualitative information about main and co-products transferred into quantitative data.

Information Regarding Production as Main or Co-Product	Quantitative Value
Only main product	0
Mostly main product	0.33
Mostly co-product	0.67
Only co-product	1

2.2.7. Storage Complexity

The produced materials and (intermediate) products might have to be stored before they are used. Depending on the characteristics of the material it can be difficult to provide adequate storage conditions. For example, some agricultural products need to be refrigerated and/or turned over for air circulation. The complexity of storage can lead to possible restrictions to availability as the biotic materials can decompose and therefore cannot be used further. It is relevant for all supply chain stages. Storage has to be provided for biotic resources as well as man-made biotic materials because both are stored during their life time. The moisture content of the material and (intermediate) product can be related to most of the storage challenges, e.g., insect infestation, fungal growth and turn-over of the goods [56–58], so it is used as an indicator to describe storage complexity. When the moisture content is low (and therefore there is less water in the product) the complexity of storage decreases. The moisture content can differ depending on the country where the biotic material is cultivated and stored as the humidity in different countries varies. Hence, if data is available, the moisture content of a biotic material should be determined for every storing country individually. Since the successful storage also highly depends on the countries development [59], the economic vulnerability of the country where the material or (intermediate) product is being stored is also taken into account. Economic vulnerability refers to the weakness of a country to absorb and overcome severe shocks while supporting strong economic growth [60]. It is assumed that a country with a low vulnerability is also able to handle complex storage of materials and (intermediate) products. Thus, the Economic Vulnerability Indicator (EVI) by Organization for Economic Cooperation and Development—OECD (2016) [60] is used as the basis for quantification. The storage complexity is determined by multiplying the global production share (sgp) with the EVI. Furthermore, the value is added to the moisture content (mc) (see Equation (7)). Both components can range from 0 to 100 and thus equally influence the result.

$$\mathrm{SC_i} = \mathrm{mc_{i,x}} + \sum\left(\mathrm{sgp_{x,i}} \times \mathrm{EVI_x}\right) \tag{7}$$

2.2.8. Recycling

During production of (intermediate) products primary as well as secondary materials might be used. If more secondary materials are utilized less primary materials have to be produced. Thus, the demand for primary materials is reduced and the overall availability increases. The higher the recycled content of a product is, the less primary material has to be harvested. To determine the primary material use (PMU) the recycled content of a product (given in percentage) is subtracted from 100% (see Equation (8)).

$$\mathrm{PMU_i} = 100\% - \text{recycled content}_\mathrm{i} \tag{8}$$

2.2.9. Determination of Characterization Factors

Based on the method by Bach et al. (2016) [28] for abiotic resources the determined indicator values are transferred into characterization factors (CFs) using the Distance-to-Target (DtT) approach. In the following this 4-step DtT approach is introduced:

(Step 1) For all categories indicator values have to be determined (as shown in Sections 2.2.1 and 2.2.8) for the materials of the study.

(Step 2a) Targets for all categories have to be determined. For nine of the ten categories targets are already established in the approach for abiotic materials. These targets can be used for the assessment of biotic materials. The approach how the target values were established can be found in the publication by Bach et al. (2016) [28]. These values are introduced as default values. Thus, they can be adapted by practitioners and stakeholders according to their preferences. There is no target for the category storage complexity available because the category was not considered in the approach for abiotic materials. Thus, a target value is set to 60 for the category. This value is not established based on stakeholder survey or expert judgment, but only by the authors to show the applicability of the DtT approach for BIRD. The value of 60 was considered reasonable as it is assumed that a moisture content of 30% as well as a vulnerability of 30 (based on the global production of a material and the corresponding EVI) can be seen as potentially limiting the availability of biotic materials significantly.

(Step 2b) Based on the ecological scarcity approach by Müller-Wenk et al. (1990) [61] and Frischknecht et al. (2009) [62] the indicator values are set in relation to the target to determine the DtT value for each material i in each category c (see Equation (9)). Is the DtT value lower than 1, no constraints on availability can be expected. Thus, the DtT value is set to zero. If the DtT value is equal 1 or greater than 1 possible availability restrictions might occur. The ratio of the current to the critical flow is squared to weigh the exceeding of the target above proportional [62].

$$\mathrm{DtT} - \mathrm{value_{i,c}} = \left(\frac{\text{indicator value}_\mathrm{i,c}}{\mathrm{target_c}}\right)^2 \tag{9}$$

(Step 3) To take the overall amount of the material currently produced into account, the DtT values are normalized (nDtT) (see Equation (10)). For raw materials with small amounts of production, e.g., cotton, the restrictions quantified in the ten categories can be even more significant compared to materials for which the overall annually produced amount is higher, e.g., wheat.

$$\text{nDtT value}_{i,c} = \frac{\text{DtT value}_{i,c}}{\text{normalization value}_i} \tag{10}$$

(Step 4) The nDtT values are expressed in small numbers which are challenging for the application within the LCA framework (in LCA the characterization factor is multiplied by the amount of the material in the product system). Thus, they are scaled to 6.3×10^{15} (this number was chosen as it presents the highest global production value of total grains in the year 2015 according to United States Department of Agriculture (USDA) [63]. According to Equation (11) the final CFs are calculated. The highest value of each category (nDtT $\text{value}_{c,i,max}$) is set to 6.3×10^{15}. The CFs of the other materials are calculated by applying the rule of three [64]. In the case study, the application of this approach is demonstrated.

$$\text{CFs}_i = \begin{cases} \text{nDtT value}_{c,\ i,\ max} \rightarrow 6.3 \times 10^{15} \\ \text{other values of category are calculated} \rightarrow \frac{6.3 \times 10^{15}}{\text{nDtT vlaue}_{c,\ i,\ max}} \times \text{nDtT value}_{c,\ i} \end{cases} \tag{11}$$

2.3. Abiotic Constraints

Abiotic constraints refer to abiotic factors influencing the ecosystem at the location where the species used as biotic material grows. Several abiotic constraints influence the environment where species used as biotic materials grow (see Figure 5). They are divided into 'constraints on the ecosystem' and 'limiting factors: resources needed for cultivation'. Some of these constraints impact the availability of species used as biotic materials locally, others more globally. They are equal for biotic resources and man-made biotic materials.

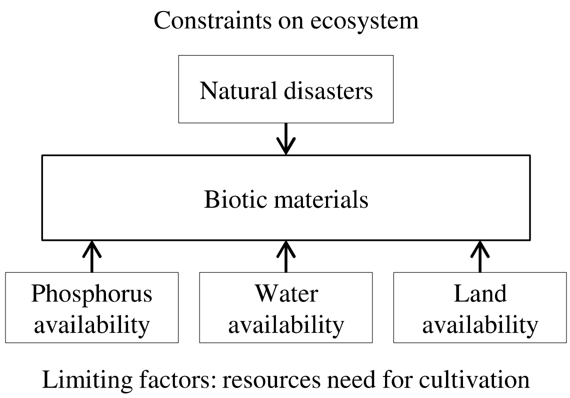


Figure 5. Overview of abiotic aspects impacting biotic materials.

Water availability is one very dominant aspect since over 70 percent of all water resources worldwide are used for agriculture purposes [65]. Thus, the cultivation and harvest of species used as biotic materials highly depend on the local water scarcity, which is influenced by local precipitation, run-offs evapotranspiration and consumption [66,67]. When a species used as a material predominantly grows in water scare regions, the possibility of restricted availability is higher than for species grown in water rich regions [68]. Methods to assess water scarcity of bio-based products systems exist and have been tested in several case studies, e.g., [69,70]. To determine possible restrictions to availability due to water scarcity (WS), the global production share (gps) of a biotic material i is multiplied with the water depletion index (WDI) by Berger et al. (2014) [71] and summed up according to Equation (12).

$$WS_i = \sum (gps_i \times WDI_x) \tag{12}$$

The higher the WS_i, the higher are the potential restrictions to availability for a biotic material. Water availability is especially important for the cultivation stage as species used as biotic materials need water to grow. However, lack of available water can also impact other supply chain stages, e.g., when industrial processes require large amounts of water.

Furthermore, land and phosphorus availability can be constraints for accessibility of species used as biotic material. Currently enough land and phosphorus are available for cultivation of species used as biotic materials. However, several studies predict (e.g., [71–78]) that with increasing use of biotic materials (e.g., for biofuels) in the next decades not enough land and phosphorus will be available to meet all human needs (e.g., for food, feed and industrial processes). However, both challenges are rather universal and are less related to one specific species used as a biotic material [79,80]. Only phosphorus and no other soil nutrients are considered, because phosphorus is a limited resource itself and thus can limit the production of agricultural products significantly. Other nutrients like potassium, calcium, sulfur, magnesium and nitrogen (which can be easily extracted from the air e.g., via Haber-Bosch process [81]) are not considered being scarce as they are available in great quantities within nature or can be easily recycled [82–84]. Thus, limitations to their availability are not expected in the near future and, therefore, not included within this approach.

Phosphorus amounts used in the cultivation stage are reported frequently in case studies focusing on agricultural systems (e.g., [85–87]). To assess land use and accompanied environmental impacts, several methods exist (e.g., [26,88,89]). Often, the overall area in hectare per year (ha/year is also reported. However, these methods have so far only been used in the context of assessing the impacts of a product system, but not for the evaluation of possible restrictions to the availability of species used as biotic materials.

The use of land and phosphorus to produce species used as biotic materials is considered within the BIRD method by reporting the amount of the land used (in h/year) and phosphorus applied (in kg) in a specific product system. Thus, by comparison of two or several product systems a statement is possible regarding the land and phosphorus use. The amount of land use for the cultivation of a specific species used as a material (with regard to the functional unit) can be determined either by measurements provided by the practitioner (e.g., farmer) or average values based on literature research or within common LCA databases like GaBi [90] and ecoinvent [91]. For the determination of phosphor use either measured values provided by the practitioner (e.g., farmer) or average values based on literature research can be used [92].

Another abiotic constraint is the occurrence of natural disasters. Natural disasters can affect regions by floods (FL), droughts (DR), hurricanes, earthquakes, volcanic eruptions, forest fires, landslide, pests and diseases [93]. In the last years natural disasters have impacted the agriculture dramatically: around 30% of all agricultural products were destroyed by natural disasters between 2003 and 2013 [94]. Especially droughts and floods play an important role with regard to agricultural product loss, whereas volcanic eruptions, earthquakes, hurricanes, forest fires, pests and diseases—even though have dramatic outcomes when they occur [95]—do proportionally not destroy as much agricultural products [93,94,96,97]. Natural disasters are monitored and reported by several organizations (e.g., [98,99]). However, these factors are so far only being applied for monitoring purposes, but not in the context of assessing possible limitations to the availability of biotic materials.

For the quantification of the influence of natural disasters on the availability of biotic materials within the BIRD method the natural disaster risk (NDR) indicator is determined on country level based on data by (United Nations Office for Disaster Risk Reduction 2013) [100]. The impacts within a specific region x are summed up and multiplied with the global production share of the material considered (see Equation (13)). The higher the NDR_i the more likely are possible restrictions to availability of biotic materials. Natural disasters can affect biotic resources as well as man-made biotic materials. For the supply chain stage, cultivation and harvesting natural disasters are predominantly important. However, they might also affect other supply chain stages, when, e.g., producing plants are destroyed by floods.

$$NDR_i = \sum gps_{i,x} \times (FL_x + DR_x) \tag{13}$$

2.4. Social Constraints

Social constraints refer to societal aspects which limit the availability of resources and man-made biotic materials. For once the "Food first" principle has to be considered when assessing availability of biotic materials. The main function of biotic materials as an agricultural product is to provide food for human consumption. The use in industrial processes can only be an option, when food security in all countries is guaranteed [100]. As of today several studies exist discussing food security in the global context. Most studies agree that currently no food crises is initiated due to biotic material use in the industrial sectors, but rather socio-economic aspects in the countries are responsible for food scarcity [101]. However, when demand of biotic materials significantly increases, food security could be impaired. So far there are no methods to estimate if biotic materials violate the "Food first" principle. To comply with the "Food first" principle it has to be ensured that the used biotic material is not traded by a country where food crises occur. Thus, for the assessment within the BIRD method an indicator is introduced to measure the risk of a material to be exported by a country, which cannot ensure food security. This indicator is determined according to Equation (14), where the global production share (pgs) of a material i is multiplied by the food security index (FSI) [102] of the related country x and then summed up (see Equation (14)). The FSI is created based on the food security indicators (e.g., depth of the food deficit, cereal import dependency ratio, etc.) by FAO (2016) [102] (see supplementary material—Section 2 on how the FSI is constructed). The food first principle is important for man-made biotic material as they are used for food and feed. Thus, the supply chain stages nature, cultivation and harvesting are impacted.

$$FSI_i = \sum (gps_i \times FSI_x) \tag{14}$$

Furthermore, social constraints can also occur due to lacking societal acceptance with regard to a company's compliance of social standards. The consumers' perception of the company has been influencing the decision to buy products more and more in the recent years [103,104], e.g., consumers boycotted blueberries due to poor working conditions of farm workers [105]. In the worst case, a certain material cannot be used by a company because of its low societal acceptance, even though it is available from a physical and socio-economic perspective. Furthermore, societal dismissal can also occur with regard to compliance with environmental standards, e.g., consumers are boycotting palm oil as it is seen as one major contributor in destroying orangutan habitats [106]. Bach et al. (2016) [28] developed an approach to measure the compliance with social standards based on data by Social Hotspot Data Base (SHDB) [107,108] and with environmental standards based on the Environmental Performance Indicators (EPI) by [109] for abiotic resources.

To determine the compliance with social standards aspects with low societal acceptance are identified as child labor (CL), forced labor (FL) and high conflict zones (CZ). For these aspects data from the SHDB [107,108] is identified. The SHDB provides data on country and sector level. Several sectors are available for the evaluation of biotic materials (including crops, food products, oil seeds, plant based fibers, sugar cane, vegetables and wheat). Based on the product system under investigation the appropriate sector/s have to be identified by the practitioner. The screening indicator for a material i is determined by multiplying the three social hotspot indexes with the global production shares (sgp) x and summing them up (see Equation (15)). Compliance with social standards is important for biotic resources as well as man-made biotic materials and play a role in all supply chain stages as within every stage child labor, forced labor and high conflict zones may occur.

$$SC_i = \sum[sgp_x \times (CL_x + CZ_x + FL_x)] \quad (15)$$

For the quantification of compliance with environmental standards the EPI [109] is applied. The EPI provides 16 sub indicators measuring the performance of countries regarding their environmental protection efforts including protection of biodiversity. Therefore, the sub indicators Critical Habitat Protection (CHP), Marine Protected Areas (MPA) and Terrestrial Protected Areas (TPA) are used to determine the compliance with environmental standards. It is assumed, that the manner of a country taking care of its biodiversity is similar to the overall compliance with environmental standards. The compliance with environmental standards (EC—environmental compliance) is determined by multiplying the global production shares of the countries (gps_x) with the EPI indicators and summing it up (see Equation (16)).

$$EC_i = \sum[sgp_x \times (CHP_x + MPA_x + TPA_x)] \quad (16)$$

Compliance with environmental standards is important for biotic resources as well as man-made biotic materials. For both the extraction and cultivation can occur with high loss of biodiversity, which is of more concern to consumers as gradual pollution of the environment over time and therefore indirect loss of biodiversity. Thus, species used as biotic materials causing direct loss of biodiversity have a higher potential restriction as species causing indirect loss of biodiversity. Environmental compliance plays a role in all supply chain stages as within every stage environmental pollution can occur. However, as the direct loss of biodiversity (which mostly occurs due to harvesting of agricultural plants) is seen as more severe by consumers the supply chain stage harvesting is of most concern.

2.5. Environmental Constraints

Environmental impacts of species cultivation, extraction and use can lead to various impacts, which can change the ecosystem significantly up to the point where the cultivation of species used as biotic materials and thus the availability of these materials is jeopardized [11,110]. Emissions during cultivation, extraction and use (as well as the end of life) can lead to direct and indirect pollution of the environment (e.g., acidification, eutrophication, etc.) including degradation of soils, contamination of freshwater, etc. which are extremely important for the successful and efficient cultivation of species used as biotic materials (see Figure 6) [111].

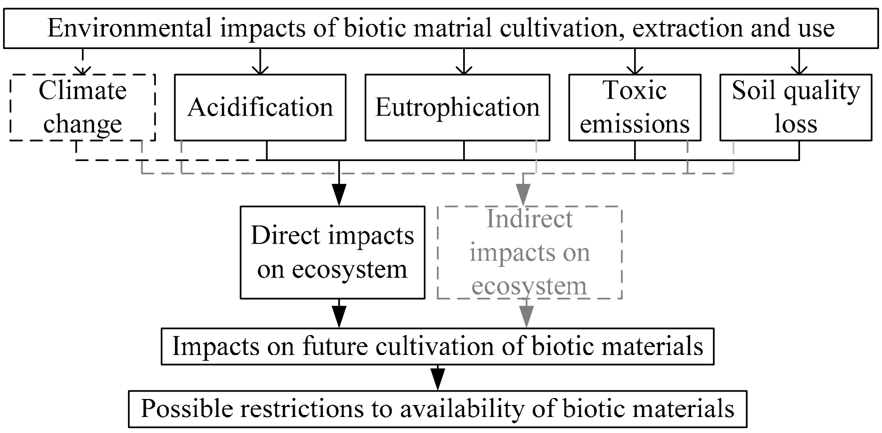


Figure 6. Overview of cause-effect-chain with regard to environmental impacts and restrictions to availability of biotic materials.

Thus, environmental impacts can constraint the availability of biotic materials. The LCA method has been used for decades to assess environmental impacts over the entire life cycle of products [38]. Several methods exist within the LCA framework assessing impacts to water, soil and air, e.g., [37]. For the assessment of biotic materials, following aspects are relevant and should be considered: impacts into soil, water and air (like eutrophication, acidification and toxicity) as well as resulting impacts like soil quality loss and biodiversity loss. Furthermore, impacts due to land use and land use change have to be taken into account. Climate change is taken into account as one of the most important prospective factor regarding changes in ecosystems. These changes can lead to a reduced availability. Several studies confirm that climate change leads to, e.g., extreme weather events influencing the availability of agricultural products (e.g., [112–114]).

However, not for all these aspects mature methods are available. As shown by [115–117] several methods have high uncertainties and thus, have to be applied with caution. However, in the current work of the UNEP/SETAC Life Cycle Initiative some more mature methods are developed [118]. Currently several impact assessment methods are tested in the Product Environmental Footprint (PEF) initiative [119]. In case these methods are evaluated to be mature enough for implementation, they should be added to the ones proposed here. For the BIRD method it is recommended to only use mature impact assessment methods to ensure adequate decision making. These mature methods are CML-IA [37] for acidification, eutrophication and photochemical ozone formation, the Intergovernmental Panel on Climate Change (IPCC) method for climate change [120] and the World Meteorological Organization (WMO) method for ozone depletion [121]. Environmental constraints are important for species used as biotic resources as well as man-made biotic materials as for both of them the underlying ecosystem can be affected. Even though these environmental impacts can occur over the whole supply chain, there are mostly affecting the supply chain stages ‘nature’ and ‘cultivation and harvest’. However, the other supply chain stages can be affected also indirectly; e.g., when due to water pollution (e.g., acidification, eutrophication) not enough clean water is available for industrial processes. Even though the state of the environment is directly related to the availability of species used as materials, it is so far not determined to which extend. Emitting twice the greenhouse gases will not lead to double the restrictions to availability. Thus, the LCIA results cannot be directly related to the potential restrictions to availability. However, as a first approach the principle “less impacts, less constraints” is used.

3. Case Study

In the following the BIRD method is applied in a case study. For simplicity only two materials are considered. For the case study 1 L biofuel made from rapeseed or soy beans is analyzed. For both plants the cultivation and harvest of the agricultural products as well as all processing steps are taken into account.

3.1. Physical Constraints

The considered biotic materials can be classified as man-made (and are therefore not a biotic resource). These plants might be also available within nature, but are not being harvested to produce biofuels in this case. Thus, resource depletion is not considered (an example how to calculate the BRA for a biotic resource is included in the Supplementary Materials—Section 3.1.1). Physical limitations on man-made biotic materials include anthropogenic constraints as well as restrictions due to replenishment rate. The replenishment rate is determined according to Figure 4. Both rapeseed and soy beans have a growth rate less than one year [122]. Furthermore, both have a high yield, which is one reason they are cultivated for producing biofuels [123]. Thus, the corresponding indicator value is zero, which means that for both plants limitations to availability due to replenishment are not a limiting factor.

To determine the anthropogenic restraints of the biotic materials the concept presented in Section 2 is applied. Data is lacking with regard to the amount of globally produced rapeseed and soy beans used for biofuel. Thus, the shares of the largest consumers of rapeseed and soy beans are applied instead based on the data by Barrientos and Soria (2016) [52]. The five biggest consumers of rapeseed are EU, Canada, China, USA and India: for soy beans USA, Brazil, Argentina, China and EU can be identified [52]. In the considered countries rapeseeds and soy beans are used for food, feed and fuel production [124,125]. No data was found stating if soy beans and rapeseeds are used within any products or for biofuels only. However, if they are used for products the amount is most likely very small and would not change the overall result significantly. As the factor for both materials in all considered countries is 1, the overall anthropogenic constraints result in 1 as well (for more details see Supplementary Materials—Section 3.1.2). Both materials are predominantly used for biofuels, food or feed and thus are consumed and cannot be used again (see Figure 7). Hence, they do not contribute to the anthropogenic stock.

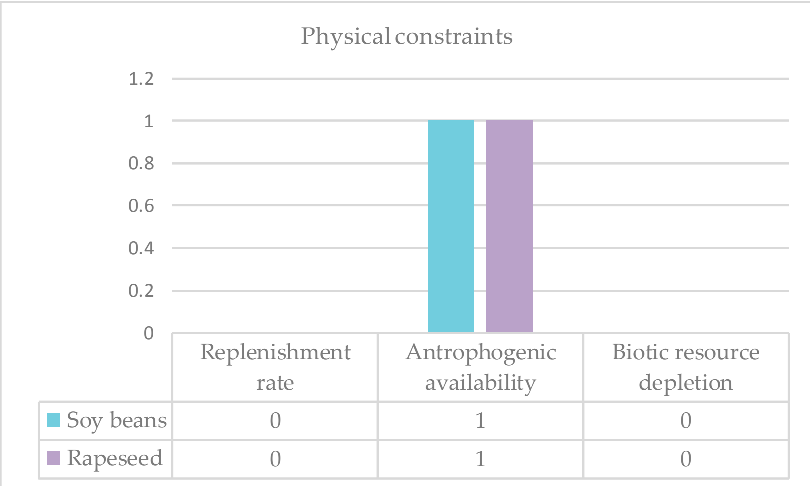


Figure 7. Results for the dimension physical availability of rapeseed and soy beans.

3.2. Socio-Economic Constraints

In the following, the results for the category indicators for the dimension socio-economic constraints are shown (detailed calculations can be found in the Supplementary Materials—Section 3.2):

Concentration of resources: This category is not considered as only man-made biotic materials are considered in the case study.

Company concentration: This category (more precise categories as company concentration plays a role in all supply chain stages) could not be determined because there is no global data available with regard to companies trading rapeseed and soy beans.

Concentration of harvesting: This category is determined for the harvesting step of soy beans and rapeseed by applying the HHI according to Equation (6) based on data by Barrientos and Soria (2016) [52]. To determine the HHI the global production shares are squared and summed up. For soy beans the HHI is 0.25 and for rapeseed it is 0.13. Only three countries (USA, Brazil and Argentina) produce around 82% of all soy beans worldwide [52]. For rapeseed the three biggest producers (Canada, China and EU) worldwide add up to around 78% [52]. However, as within the EU overall 26 countries produce rapeseed [52], the HHI is lower as for soy beans. Thus, potential limitations to availability due to concentration of harvesting are higher for soy beans than for rapeseed. However, considering the target value of the category (0.15) potential restrictions occur only for soy beans.

Political instability: Political instability determined according to Equation (3) can occur during the cultivation as well as during processing of the materials and production of biofuel. It is determined by multiplying the global production or consumption share [52] with the WGI [49]. For the cultivation and harvesting step global production data [52] are used whereas global consumption data [52] are applied for the processing and the final product step. For the production step the political instability is

1.9 for soybeans producing countries and 1.4 for rapeseed producing countries. For soybeans the three countries with the highest production contribute most to the result: Brazil, Argentina and USA [52]. However, especially the contribution of Brazil and Argentina is significant since their WGI values are high [49]. For rapeseed, China influences the result the most, even though it is only the third biggest producing country (next to Canada and the EU). Thus, possible limitations to availability due to political unstable countries are higher for soy beans than for rapeseed. When considering the target value (1.9) potential restrictions occur only for soy bean. It is assumed that soybeans and rapeseed are pressed into meal and oil, which are further processed into biofuel within the same country. This assumption is made as global data regarding rapeseed and soy bean oil (and meal) production is not available. Thus, the political instability can be determined once for both steps using the global consumption share based on data by Barrientos and Soria (2016) [52]. For the processing and product step limitations due to political instability for rapeseed add up to 1.3, whereas for soy beans the limitations are lower with 2.1. The biggest consuming country of soy beans is China [52], which also has a high WGI [49]. For rapeseed the biggest consuming country is also China [52]. Considering the target value (1.9) only for soy beans potential restrictions to availability occur. However, compared to the cultivation and harvesting step, the possible limitations are higher within the processing and product step.

Demand growth: The demand growth for the cultivation stage is calculated according to Equation (4) based on USDA (2016) [126] providing annual production data of soy beans and rapeseed. The demand growth is 7.6% for soy beans and 2.6% for rapeseed. Annual production data are used to determine the demand growth in the processing step based on USDA (2015) [127] for all countries producing biodiesel out of soy beans and rapeseed. The demand growth for soy beans is 8.9%. For rapeseed the demand growth adds up to 1.6%. Therefore, the possible restrictions to availability due to demand growth are much higher for soy beans than for rapeseed. Furthermore, for soy beans the demand growth of the processing step where biodiesel is produced is higher than for the soy bean production itself. Since the demand growth of both materials in the considered supply chain stages is above the target (5%), potential restrictions to availability occur for both materials.

Trade barriers: Trade barriers are determined by multiplying the global production shares [52] with the ETI [50] and aggregating the values (see Equation (5)). Trade barriers can occur when soy beans and rapeseed are harvested and exported for further production as well as when biodiesel is produced. Trade barriers are sum up to 3.4 for soy beans and 2.4 for rapeseed. For rapeseed the country influencing the result the most is China, as it is one of the biggest producers [52] and has several trade restrictions [50]. For soy beans the country with the biggest influence is Brazil. Considering the target value (3.15) potential restrictions to availability occur only for soy beans. For the processing step trade barriers are determined using country consumption data [52] and summed up to 3.2 for soy beans and 2.2 for rapeseed. Here China has the highest influence both for rapeseed and for soy beans. Considering the target value (3.15) potential restrictions to availability occur only for soy beans. Thus, the potential restrictions to availability due to trade barriers are higher for soy beans than for rapeseed within all stages. Furthermore, restrictions are higher for countries cultivating the species used as biotic materials than for countries producing biodiesel.

Price fluctuations: As sufficient data regarding the monthly prices over the last five years are not available for soy beans and rapeseed, the commodity prices index published by Barrientos and Soria (2016) [52] is used to assess price fluctuations for rapeseed oil and soy bean oil (processing step). The commodity price index is an average of selected commodity prices based on monthly or daily prices over the period of several months [52,128]. Prices for soy bean oil vary much more (7.1%) than prices for rapeseed oil (2.7%). Thus, possible restrictions to availability due to price fluctuations are higher for soy bean oil than for rapeseed oil. Data regarding the price fluctuations of rapeseed and soy beans as well as biodiesel are not accessible. Since both materials are below the target (20%), potential restrictions to availability do not occur for both materials.

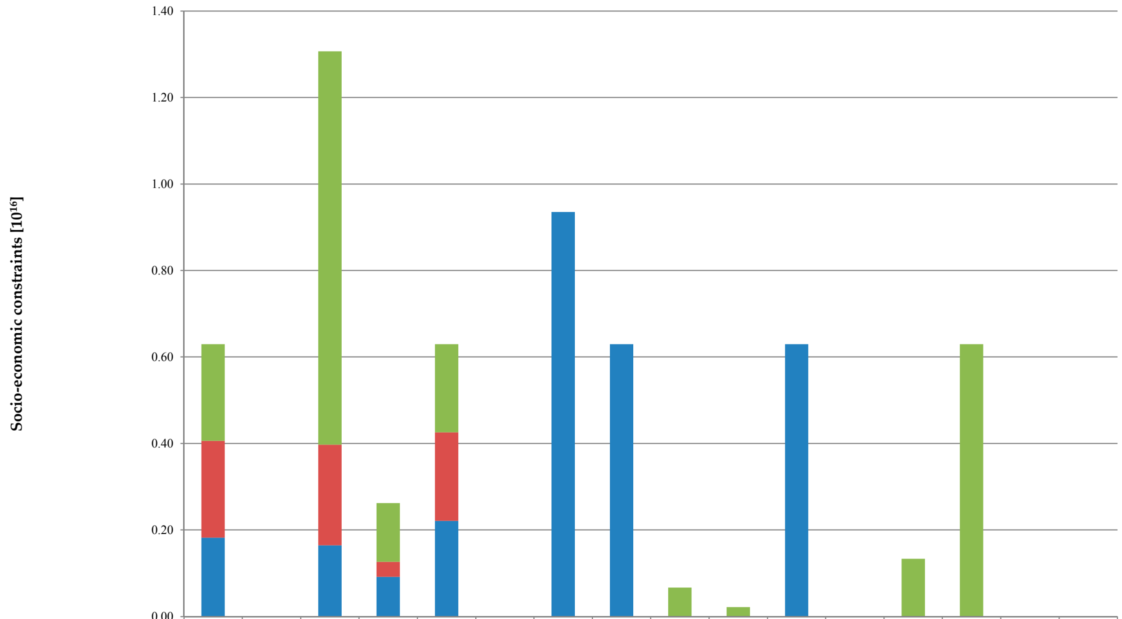
Occurrence as co-product: When considering the supply chain of soy beans and rapeseed, co-product occur within every stage. After harvesting straw is left, which often remains on the field, but can also be used to produce second-generation biofuels [129]. During processing soy beans and rapeseed are pressed into oil and cake [130]. The oil is being processed further into biofuel by e.g., refinement of oils, transesterification, etc. In all these process steps co-products occur [130]. To determine if possible restriction to availability, all products need to be classified as shown in Table 3 for every supply chain stage. Both materials can be classified as 'only main product' for the harvesting step. Even though the straw can be used for production of second-generation biofuels, the main products are still the soy beans and rapeseed. Thus, both materials get assigned the value of zero. For the next step—material pressing—the co-product cake is an important product for animal feed and thus, soy bean and rapeseed oil are classified as 'mostly main products' (value of 0.33). Even though several co-products are generated during the biodiesel production, the main product is still biodiesel and thus it can be classified as 'only main product' (value of zero). There is no difference for soy beans and rapeseed as both are processed into biodiesel in a similar way. Since both materials are below the target, no potential restrictions to availability occur.

Storage complexity: This category has to be determined for the storage of soy beans and rapeseed as well as for the storage of the produced oils and biodiesel. However, as the products oils and biodiesel can be stored for a long time and both have a high economic value [131], it is assumed that no potential restrictions due to storage complexity occur. To determine possible restrictions for soy beans and rapeseed Equation (7) is applied by multiplying the global production shares [52] with the EVI [60] and aggregating the results. Furthermore, the moisture content of the material in storage is taken into account. For soy beans and rapeseed the average moisture content during storage is 11%–15% [132,133]. Thus, the average of 13 is used for the calculation. The results for the storage complexity for soy beans is 20.8 and for rapeseed 44.0. As the countries storing soy beans have a low economic vulnerability the influence of the moisture content is more significant. For rapeseed the countries storage ability has a higher influence than the moisture content, with China being most influential. Thus, the potential restrictions to availability due to high storage complexity are higher for rapeseed than for soy beans. However, since both materials are below the target (60), no potential restrictions to availability occur.

Recycling: This category is applied for the final product. As biodiesel is burned and thus cannot be recycled [134], the recycled content is zero for both biotic materials and thus the PMU is 100% (see Equation (9)). Since both materials are above the target, for both, potential restriction in terms of availability occurs.

Next to the calculation of the indicator values, the DtT approach is also applied for better interpretation of the results. To implement the Distance-to-Target (DtT) approach the determined indicator values for the case study are set into relation to the target to determine the DtT value according to Equation (8). Next, the DtT values are normalized according to Equation (9). Finally, the results have to be rescaled to the 6.3×10^{15} according to Equation (10) (for detailed calculations please see Supplementary Materials—Section 3.2.6).

In Figure 8, the results for all supply chain stages and both evaluated materials are shown. It can be seen that demand growth and price fluctuation are the biggest restrictions for soy bean availability. For the availability of rapeseed price fluctuations and recycling have the most influence. The cultivation and harvesting step is mostly impacted by price fluctuations, concentration of harvesting and trade barriers. Demand growth and recycling mostly influence the availability of the final product biodiesel. Limitations in the processing step (oil production) are comparably low.



	Political instability		Demand growth		Trade barriers		Price fluctuations		Occurence as co-product		Concentration of harvesting		Recycling		Storage complexity	
	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds	Soy beans	Rapeseeds
(intermediate) product	0.22	0.00	0.91	0.14	0.20	0.00	0.00	0.00	0.07	0.02	0.00	0.00	0.13	0.63	0.00	0.00
Process step	0.22	0.00	0.23	0.03	0.20	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
Cultivation and harvesting step	0.18	0.00	0.16	0.09	0.22	0.00	0.94	0.63	0.00	0.00	0.63	0.00	0.00	0.00	0.00	0.00

Figure 8. Results for the dimension socio-economic constraints for all supply chain stages.

3.3. Abiotic Constraints

In the following, abiotic constraints to the product systems are determined. For limitations due to water availability Equation (12) is applied for the supply chain stage cultivation by multiplying the global production shares [52] with the WDI [69] and aggregating the results (for more information see Supplementary Materials—Section 3.3.1). The water availability adds up to 0.33 for both materials. Thus, possible limitations to availability due to water scarcity are the same.

Furthermore, restrictions due to natural disasters are determined for the supply chain stage cultivation) by multiplying the global production shares [52] with the NDI [98] and aggregating the results (for detailed information see Supplementary Materials—Section 3.3.2). For soy beans, the natural disaster risk adds up to 16.8. For rapeseed, the overall risk is 10.8. Thus, potential restrictions to availability are higher for soy beans than for rapeseed.

Land use and phosphorous input can be determined carrying out an LCA. As this would go beyond the scope of this article, existing studies are used. Based on Zulka et al. (2012) [86] land used for cultivation of rapeseed is 7.7 m^2/year per liter biofuel. For soy beans, the land use is 7.6 m^2/year per liter biofuel based on Pradhan et al. (2012) [85]. As the results are not from the same study, they should not be compared (e.g., due to different system boundaries, etc.). However, to show how the results would be interpreted we still use them here for an exemplary comparison. Based on the results, possible limitations to availability are higher for soy beans than for rapeseed. With regard to phosphorus use the phosphor input for rapeseed cultivation is 4250 g/L biofuel [86] whereas it is only 9.64 g/L for soy beans [85]. Thus, the possible restrictions for rapeseed are much higher than for soy beans. However, it has to be considered again, that the results of two different studies were taken into account. Especially for soy beans, amounts of phosphorus inputs differ widely depending on the study [85,135,136].

As the categories within this dimension have different units they cannot be compared directly (e.g., the amount of phosphorus of soy beans cannot be compared with the water availability of rapeseed).

Thus, for better visualization within a diagram the comparison is based on shares (see Figure 9), where the higher result within a category is set to 1 and the other result is calculated accordingly.

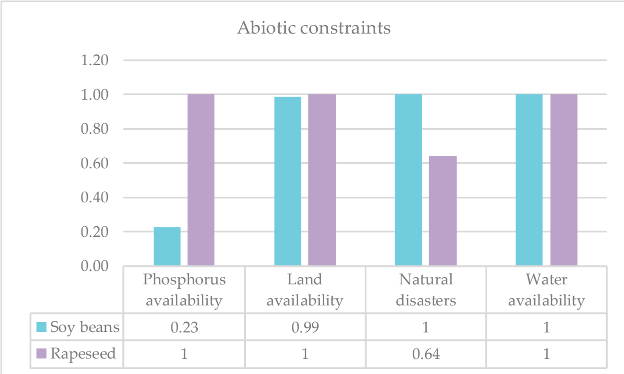


Figure 9. Results for the dimension abiotic constraints of rapeseed and soy beans.

3.4. Social Constraints

Next, social constraints for the product systems under assessment are evaluated. To determine if both systems comply with the "Food First" principle, the global production share [52] are multiplied with the FSI [102] according to Equation (14) for the supply chain stage cultivation (for detailed information see Supplementary Materials—Section 3.4.1). The food security adds up to 25.4 for soy beans and to 19.1 for rapeseed. Thus, potential restrictions to availability due to countries not complying with the food first principle are higher for soy beans than for rapeseed. To determine the compliance with social standards during cultivation and harvest data regarding child labor, forced labor and conflict zones from SHDB [108] is identified and applied according to Equation (15) based on data from Barrientos and Soria (2016) [52] and Norris et al. (2013) [107] (for detailed information see Supplementary Materials—Section 3.4.2). The social acceptance adds up to 9.0 for soy beans and to 7.0 for rapeseed. Thus, potential restrictions to availability due to non-compliance with social standards are higher for soy beans. To determine the compliance with environmental standards (cultivation and harvesting) EPI data [109] are identified on country level. The environmental compliance is determined for the supply chain stage cultivation and harvest according to Equation (16) based on data from Barrientos and Soria (2016) [52] and Yale Center for Environmental Law and Policy (2014) [109] (for detailed information see Supplementary Materials—Section 3.4.2). The non-compliance with environmental standards adds up to 11.0 for soy beans and to 11.2 for rapeseed. Thus, potential restrictions to availability due to non-compliance with environmental standards are similar for both.

Similar to the results of the dimension abiotic constraints, the results of the dimension social constraints cannot be compared directly. Thus, a comparison based on shares is performed (see Figure 10).

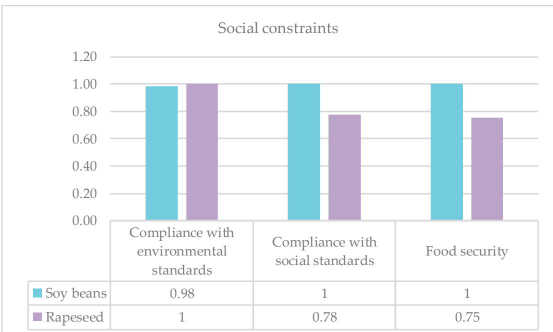


Figure 10. Results for the dimension social constraints of rapeseed and soy beans.

3.5. Environmental Constraints

To determine environmental constraints an LCA case study has to be carried out. Again, existing case studies are used as performing an own case study is beyond the scope of this article. As the results for environmental impacts of soy beans and rapeseed are not taken from the same study, they are difficult to compare (e.g., due to different system boundaries etc.). However, as stated before, we still use them here for an exemplary comparison to show how the results can be interpreted. Considering the study of Panichelli et al. (2009) [135] for soybean-based biodiesel and by González-García et al. (2013) [137] for rapeseed-derived biodiesel results for the three impact categories climate change, eutrophication and acidification can be obtained. Other case studies had to be used as for identifying the amount of phosphorus and land use since these studies did not contain results for the desired impact assessment categories. Based on this data, the production of biodiesel made from rapeseed leads to less environmental impacts than the biofuel production made from soybeans. However, it has to be considered, that results of two different studies are taken into account. Thus, the results should be validated and are only used here to demonstrate the introduced approach. Even though impacts are determined over the whole life cycle, they are mostly affecting the cultivation stage since the environment pollution leads to ecosystems changing and thus possible restrictions in the availability of species used as biotic materials. However, as stated before, no direct correlation between environmental impacts and limited availability can be made, as the amount of emitted substances (or the impact assessment results) cannot be related to a certain restriction in availability. Thus, the "less impacts, less constraints" principle is applied for now.

Summarizing, for most categories the possible restrictions to availability are higher for soy beans than for rapeseed within all considered supply chains stages (see Table 4). Exceptions are the category recycling for the stages processing of oil and final biodiesel production as well as phosphorus use and land availability for rapeseed. Data for the supply chain stage cultivation and harvest was easier to collect than for the other supply chain stages. However, it was demonstrated that the introduced approach can be applied and leads to plausible results which can be interpreted.

Table 4. Results for physical, socio-economic and abiotic constraints of soybeans (SB) and rapeseed (RS) for the considered categories in the corresponding supply chain stages.

Dimension	Category	Supply Chain Stage			
		Nature	**Cultivation and Harvest of Soy Beans and Rapeseed**	**Processing (and Corresponding Steps) of Soy Beans and Rapeseed**	**Production Steps to Produce Biodiesel**
Environmental constraints	Acidification Eutrophication Climate change		SB > RS SB > RS SB > RS		
Social constraints	Compliance with environmental standards		SB = 11.0 RS = 11.2		
	Compliance with social standards		SB = 9.0 RS = 7.0		
	Food security		SB = 25.4 RS = 19.1		
Abiotic constraints	Phosphorus availability		SB = 9.64 RS = 42.5		
	Land availability		SB = 7.6 RS = 7.7		
	Natural disasters		SB = 16.8 RS = 10.8		
	Water availability		SB = RS = 0.33		

Table 4. *Cont.*

Dimension	Category	Supply Chain Stage			
		Nature	**Cultivation and Harvest of Soy Beans and Rapeseed**	**Processing (and Corresponding Steps) of Soy Beans and Rapeseed**	**Production Steps to Produce Biodiesel**
Socio-economic constraints	Recycling				SB = 1.3×10^{15} RS = 6.3×10^{15}
	Storage complexity		SB = 0 RS = 0		
	Concentration of harvesting		SB = 9.4×10^{15} RS = 0		
	Occurrence as co-products		SB = 0 RS = 0	SB = 6.7×10^{14} RS = 2.2×10^{14}	
	Price fluctuations			SB = 9.4×10^{15} RS = 6.3×10^{14}	
	Trade barriers		SB = 2.2×10^{15} RS = 0	SB = 2.0×10^{15} RS = 0	
	Demand growth		SB = 1.6×10^{15} RS = 9.2×10^{14}	SB = 2.3×10^{15} RS = 3.5×10^{14}	SB = 9.1×10^{15} RS = 1.4×10^{15}
	Political instability		SB = 1.8×10^{15} RS = 0	SB = 2.2×10^{15} RS = 0	
	Concentration of resources	SB = 0 RS = 0			
Physical constraints	Replenishment rate		SB = 0 RS = 0		
	Anthropogenic availability				SB = 1 RS = 1
	Biotic resource depletion	SB = 0 RS = 0			

4. Discussion

The aim of the developed approach is to assess the availability of biotic materials within 24 categories with related category indicators. The indicator values for a broad range of materials are currently not available, which limits the applicability of the method. However, as shown in the case study, the determination of indicator values is feasible.

The BIRD approach can be applied to different taxonomy levels, e.g., order, family, species etc. For the introduced example of rapeseed this would mean that besides determining possible restrictions to rapeseed in general, also possible restrictions to the availability of different rapeseed species (e.g., annual rape and summer rape, swede rape) could have be identified. Furthermore, the availability could have also been determined for a higher taxonomic level, e.g., for all brassicaceae (cabbage family). Based on current data availability the determination of possible restrictions to availability for different rapeseed species as well as for higher taxonomic level like family is challenging as data is mostly available for a group of species (e.g., rapeseed) or different plants grouped together based on their function (e.g., oilseeds) and not for their taxonomic classification.

The developed approach has several uncertainties, which have to be considered when interpreting the results. These are described in detail in the following.

4.1. Physical Constraints

The required data for the introduced BRA indicator is missing. Thus, it is hard to determine indicator values. For future measurement of biotic resources availability, the BRA should be developed further specifically for different resource groups. For example, there are a lot of methods available and being further developed for fish consumption [138,139]. Furthermore, the calculation of the BRA for two species (African elephant and Great Indian Bustard [140,141]) has shown that the influence of the TS is not as significant for the result as it was anticipated. The interpretation of the results is challenging as well because negative values can occur demonstrating stock replenishment. To quantify the influence of the replenishment rate the introduced approach needs to be refined. Currently, the growth rate is divided into three classes, which have to be validated regarding their meaningfulness; e.g., perhaps a division into more or less classes would be more precise. Furthermore, the classification in high and low yields is currently carried out based on the practitioner's judgment. Thus, more precise rules regarding the way to determine high and low yields are needed. The global increase of production and thus the globally increasing replenishment rate was not considered in the introduced approach. However, as global production amounts influence the availability this aspect should be considered in the future.

To assess whether biotic materials contribute to the anthropogenic stock, an approach based on the use of biotic materials is introduced. However, this approach should be refined. Classifying food, feed and biofuel in one category could be misleading as, e.g., in some countries oil used for frying food is afterwards used for fuel and thus contributes to the anthropogenic stock. Furthermore, it has to be factored in how often a material contributes to the anthropogenic stock. Reuse of biotic materials often goes hand in hand with a down cycling of the material quality, e.g., furniture made out of wood will most likely not be used for another furniture but will be shredded and used for particle board. Thus, biotic materials cannot be recycled without quality loss.

4.2. Socio-Economic Constraints

Some category indicators are based on existing indicators, e.g., WGI, ETI, etc., for which data is not available for every country and thus had to be determined based on existing correlations with other indicators. These calculated values are more uncertain than the provided values. For some categories, e.g., occurrence of co-product qualitative data is transformed into quantitative ones. The transformation of quantitative data can be challenging when the classification is not conclusive, e.g., when data is obtained from different sources. For the DtT approach the target value for storage capacity was defined by the authors to carry out the calculations. This target has to be redefined by expert participation.

4.3. Abiotic Constraints

For the water availability only scarcity impacts, but not socio-economic aspects are taken into account. Even though water scarcity of a region or country is important to determine water availability, socio-economic factors also play a significant role regarding accessibility of water resources [142]. With regard to natural disasters only floods and drought are currently considered. For a more comprehensive assessment other disasters should be taken into account as well. For the assessment of phosphorus and land use only the amounts are reported. This allows a comparison of two product systems. However, it is not possible to make a statement when only one system is analyzed.

4.4. Societal Constraints

The food security index is based on five indicators since sufficient data is available for these indicators. However, additional analysis is needed to check if these indicators are sufficient to realistically reflect the situation in countries. The indicator for determining compliance with social standards is based on the three aspects child labor, forced labor and high conflict zones. These indicators were chosen based on the approach for abiotic materials. Even though these aspects are important for every sector, it should be verified if the indicators are sufficient for the assessment of biotic materials as well. Furthermore, the SHDB data are only available for broad sectors but not for small sectors. Thus, societal acceptance of biofuel production could not be determined. For the compliance with environmental standards, some of the EPI are chosen to represent the compliance of a country with environmental standards. It is necessary to check if these chosen indicators realistically present a country's compliance with environmental standards.

4.5. Environmental Constraints

Environmental constrains are determined based on the results of an LCA study. First, mature methods for several important environmental aspects are missing, e.g., biodiversity loss. Second, the reported values do not allow an overall statement with regard to possible limitation to availability. It can only be determined whether the impacts to the environment are lower when two or more options are compared. Even though it can be argued that lower environmental impacts are better for the affected ecosystems, it is not possible to determine how much and even if a certain impact actually leads to restriction in availability. Determining a target value with regard to the amount of impacts which can be seen as 'not critical' is challenging as presented in recent publications related to planetary boundaries [143–145]. Furthermore, as shown by Milà i Canals et al. (2011) [146] as well as within the ongoing PEF Pilot phase [147,148], challenges with regard to data availability and quality exist for bio-based products and thus for biotic materials. Furthermore, occurrence of invasive species can also lead to reduction of species used as biotic materials [149]. However, as it is challenging to assess such effects without detailed regionalized data, it is not considered within the BIRD approach.

4.6. General

For most indicators country based values are used to determine the overall potential restrictions for a material. These restrictions however are determined globally and do not allow conclusions regarding any regional aspects. Thus, the proposed indicators are applied as screening indicators to determine hotspots. Based on the hotspots a deeper analysis with regard to the regional conditions for the specific product system should be carried out.

Established indicators as well as newly developed ones face the challenge of underlying data quality. If the data quality is poor, the indicator will have greater uncertainties as if the underlying data is good. However, established indicators, which have been used more frequently, tend to have lower uncertainties as they were improved over time. For all applied indicators, the maturity level and meaningfulness has to be validated.

All introduced indicators can be used to assess a product and its associated life cycle. However, so far the implementation of the introduced approach into LCA is not possible (except for the dimension socio-economic availability and environmental constraints), because the indicator values are not established to be multiplied with the mass of a material.

5. Conclusions and Outlook

The introduced approach significantly enhances the availability assessment of biotic materials by providing a framework, which considers a broad range of aspects in relation to availability restrictions. Overall, five dimensions and 24 categories with corresponding category indicators are introduced. A comprehensive assessment of availability aspects as well as more meaningful decision making processes are therefore possible.

The next steps should include a comprehensive analysis of the proposed category indicators (as well as underlying indicators and data). Furthermore, indicator values for several biotic materials should be calculated to enhance applicability of the approach. These indicator values should then be applied in several case studies to test and refine them. Additional steps would be, for example, determination of the missing target value and refinement of the dimension physical constraints.

As the communication of the overall 24 indicators will be challenging (especially regarding stakeholders with less experience in the field of LCA, supply risk assessment and sustainability) future efforts should include the aggregation of the indicators within the individual dimensions. Currently, the aggregation of indicators is too challenging to be achieved within this work. Despite the benefits in communication, aggregation of indicators also has several disadvantages. By aggregating the indicator values within one dimension, transparency of the results is decreased significantly, which lowers the informative value of the communicated results. Further, weighting implies that aspects can be balanced against each other, e.g., physical constraints can be compensated with fewer environmental constraints. This kind of offsetting is a purely subjective decision, for which no commonly agreed on weighting scheme exists.

The assessment of availability is often seen as a part of the resource efficiency evaluation (e.g., [12,150]). Thus, the introduced approach can be seen as a relevant step with regard to a comprehensive resource efficiency assessment of biotic materials. Since the introduced approach is partly based on the ESSENZ method (a method to determine the resource efficiency of abiotic materials) [28] it could be implemented into ESSENZ in the future.

Supplementary Materials: The following are available online at www.mdpi.com/2071-1050/9/1/137/s1, Table S1: Overview of countries consuming rape seed and soy beans, the share of the categories as determined in Table S2 (in the main part of the article) and the corresponding factor, Table S2: Data to determine the political instability of soy bean producing countries: countries, global production share and Worldwide Governance Index, Table S3: Data to determine the political instability of rapeseed producing countries: countries, global production share and Worldwide Governance Index, Table S4: Data to determine the political instability of soy bean consuming countries: countries, global consumption share and Worldwide Governance Index; Table S5: Data to determine the political instability of rapeseed consuming countries: countries, global consumption share and Worldwide Governance Index, Table S6: Data for calculating the yearly change in demand growth: year and global production, Table S7: Data to determine the trade barriers of soy bean producing countries: countries, global production share and Enabling Trade Indicator, Table S8: Data to determine trade barriers of rapeseed producing countries: countries, global production share and Enabling Trade Indicator, Table S9: Data to determine trade barriers of soy bean consuming countries: countries, global consumption share and Worldwide Governance Index, Table S10: Data to determine trade barriers of rapeseed consuming countries: countries, global consumption share and Enabling Trade Indicator, Table S11: Production data to determine Herfindahl-Hirschmann-Index for soy beans, Table S12: Production data to determine Herfindahl-Hirschmann-Index for rapeseed, Table S13: Data to determine the storage complexity of soy bean producing countries: countries, global production share and Economic Vulnerability Indicator, Table S14: Data to determine storage complexity of rapeseed producing countries: countries, global production share and Economic Vulnerability Indicator, Table S15: Indicator results of case study for considered categories and supply chain stages, Table S16: Calculation and results of DtT-value for considered categories for soy beans, Table S17: Calculation and results of normalized DtT-value for considered categories, Table S18: Overall results for the biotic materials soy bean and rapeseed for considered categories,

Table S19: Calculation and results of scaled values for considered categories, Table S20: Data for determination of the water availability of soy bean producing countries: countries, global production share and Water Depletion Index, Table S21: Data for determination of water availability of rapeseed producing countries: countries, global production share and Water Depletion Index. Table S22: Data for determination of the natural disaster risk of soy bean producing countries: countries, global production share and natural disaster index, Table S23: Data for determination of the natural disaster risk of rapeseed producing countries: countries, global production share and natural disaster index, Table S24: Data for determination of the food security of soy bean producing countries: countries, global production share and Food Security Index, Table S25: Data for determination of food security of rapeseed producing countries: countries, global production share and Food security Index, Table S26: Data to determine the societal acceptance of soy bean producing countries: countries, global production share and indicator for compliance with social standards, Table S27: Data to determine the societal acceptance of rapeseed producing countries: countries, global production share and indicator for compliance with social standards, Table S28: Data for determination of the compliance with environmental standards of soy bean producing countries: countries, global production share and Environmental Performance Indicators (EPI), Table S29: Data for determination of environmental compliance of rapeseed producing countries: countries, global production share and Environmental Performance Indicators (EPI).

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