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Critical Natural Resources: Challenging the Current Discourse and Proposal for a Holistic Definition

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Abstract: Studies on critical natural resources have grown in number over the last decade out of concern for resource availability and its potential impacts. Nonetheless, only a handful of studies explicitly define criticality for natural resources. Through a systematic literature review, we identified four main perspectives in the descriptions of critical natural resources: (1) economic importance is overemphasized at the expense of sociocultural and ecosystem support functions of natural resources; (2) a Western perspective dominates the research discourse; (3) apart from the field of economics, the debate lacks input from social sciences; and (4), non-renewable resources are overrepresented compared to renewables. Based on the current discourse and its apparent inclinations, we propose a new definition of criticality for natural resources aligned with risk theory. We argue for the need to balance out the perspectives described above to provide decision-makers with impartial information for the sustainable management of natural resources.

Keywords: critical; criticality; definition; natural capital; natural resources; raw materials; systematic mapping

1. Introduction

Natural resources are found all around us in the natural environment. However, they are only identified as such when value is attributed to them by humans [1]. The adjective "critical" has been added to natural resources increasingly often, both in scientific publications and grey literature. This comes alongside growing awareness of global trends, such as population growth, increased consumption, and pollution. Nonetheless, most often what "critical" entails is not explained and the attributive has been used interchangeably with other adjectives, such as "strategic" or "scarce", which causes confusion over its meaning [2]. Moreover, concepts such as "critical natural capital", "keystone resources", and "critical raw materials" have emerged in different scientific fields [3–5]. They all address the notion that some resources are more critical than others and that, consequently, the management of those resources requires guidance. To the extent of our knowledge, there has not been any systematic exploration of what authors mean exactly with these concepts and where their understanding is the same and where it diverges.

Criticality assessment methodologies are the main way of evaluating and communicating the criticality of natural resources. They are used as systematic screening tools to identify resources of concern. Thereby, the assessments inform and guide policy making, research and development, as well as product design [6,7]. Governmental organizations and policymakers have been actively involved in the discourse and assessments of critical natural resources, evidenced, for example, in reports by the US Department of Energy [8] and the European Commission [9]. Classifying them as critical through these assessments leads to some natural resources being prioritized over others. The discourse has influence on decision-making since the classification provides guidance for the management of natural resources. Diverging assumptions and understandings of criticality of natural resources can thus lead to different resource management and policy outcomes. Therefore, it is important to identify the main understandings and underlying assumptions captured in the different concepts.

Following this aim, the research question guiding this work is: How have critical natural resources been defined and what aspects constitute its understanding? To answer this question, this paper maps out the discourse on the criticality of natural resources. Accordingly, we investigated common grounds and divergent interpretations of the concept. The methodology of the review is presented in the following section. In the results and discussion sections, we introduce observations from the review which are directly followed by our interpretation for each insight. Several perspectives were identified in the current literature, and based on those observations, we propose a new definition of natural resource criticality.

2. Materials and Methods

We applied systematic mapping, a type of systematic literature review [10]. It is considered a suitable methodology for a transparent and reproducible review that covers multiple research fields. Compared to regular systematic reviews, a systematic map does not attempt to answer specific research questions but rather rigorously gathers and describes available information around open-framed questions [10]. The method is suited for answering policy-relevant questions, clustering knowledge, identifying knowledge gaps, specifying further (more specific) research questions, and, as is the case for this paper, developing a greater understanding of concepts. Moreover, it aligns well with Jabareen's [11] grounded theory method to contribute to the theorisation of concepts from multidisciplinary bodies of knowledge.

A brief, step-wise overview of the process we followed to develop this systematic map goes as follows: (1) establish a review team, set the scope and research question, and develop inclusion and exclusion criteria for documents; (2) document search for evidence; (3) screen documents found; (4) code evidence and store it systematically in a database; (5) describe and visualize the findings in a report [10].

The established review team consisted of the two authors with divergent backgrounds in natural and social sciences. For step two described above, we gathered documents in May 2017 by applying a similar search string to two scientific article databases: Scopus and Web of Science. The search string was carefully designed and tested with appropriate synonyms and combinations of search terms to (1) restrict the number of nonrelated articles and (2) to find as many relevant documents for our research question as possible. The latter criterion was tested by making sure a set of previously identified articles relevant to the research question were among the gathered documents. The aim of the search string was to find publications that included the keywords "natural resources", "resources", "materials", or "natural capital" in proximity to "critical", "strategic", or "key" and close to a keyword demanding an explanation (i.e., "definition" or "classification"). The exact search strings we used can be found in Appendix A. Since the search was only conducted in English, no publications in other languages were found, which is one of the limitations of this work.

The documents identified in our search were screened and selected based on their title and abstract according to predefined inclusion and exclusion criteria. Broadly, the selection criteria aimed to include documents which contained a definition or classification of natural resources. It also needed to include a description of their criticality that was not specific to one resource but generalizable to at least a set of resources. The specific exclusion and inclusion criteria can be found in Appendix B. After reading the selected documents, a reference and bibliography search was performed, where all literature citing and cited by the selected documents was screened for inclusion. The reference search, applying the same selection criteria for title and abstract, expanded the set of documents to analyse in full text from 63 to 199 documents.

Additionally, we searched through grey literature, that is, documents published in a nonstandard way for academic practices. A number of web-based databases for grey documents exist, such as www.opengrey.eu, documents.un.org, search.un.org, and publications.europa.eu. They are, nevertheless, incomplete or not functioning properly. We initially explored those databases with search strings similar to the ones defined in Appendix A. They only provided us with a handful of relevant documents. The citation and reference search we did on our gathered scientific articles included all the relevant grey documents found as well as additional ones. They included nonpublished manuscripts, reports from governmental and other organizations, conference proceedings, statutes of public law, books and book chapters, dictionary entries, and theses. The documents were selected and analysed in the same manner as the scientific journal articles.

We performed the searches and subsequent selection of documents from May to June 2017. Ultimately, 105 full-text documents were selected for further analysis. Appendix C presents a flow diagram of the number of documents in every step of the selection procedure. Appendix D lists all articles that were finally included and reviewed.

As listed above, the final step was the analysis of the selected documents by systematically coding the evidence and producing a systematic map database of coded text fragments. We used an open-source qualitative coding and analysis program called TAMS Analyzer (4.49b5ahEC, Matthew Weinstein, Kent State University, Kent, OH, USA) [12]. We followed Clapton et al.'s [13] guidelines for coding or keywording documents. Researcher triangulation lowered subjectivity in keywording by content clustering. Both authors created their own keywords based on initial analyses of each 10 documents. We discussed and merged our coding schemes to proceed in an equivalent and structured way. Halfway through the full-text analysis, we rediscussed and adjusted the coding scheme, as well as at the end. In case of doubt or disagreement, outside experts were asked for their opinion.

This resulted in the clustering of text fragments in three main topics or codes: definitions of natural resources, classifications of natural resources, and definitions and descriptions of criticality for natural resources. The third code, criticality, was subdivided into the following six subcodes: economics, environment, physical availability of resources, politics, strategy, and technology. Furthermore, each individual document was coded with the year of publication, country of first author, journal publication, and the first author's type of institution (e.g., university, private company, governmental agency, etc.). The quality of the coding process was ensured through the collaborative nature of the research. That included frequent consultation within and outside of the coding team, as well as through the documentation of procedures and decisions [13]. Text fragments, grouped by their specific codes and potential overlaps with other codes, were then analysed to reveal patterns in the data.

3. Results and Discussion

3.1. Natural Resources and Their Classification

Before being able to explore the criticality of natural resources, it is necessary to form an understanding of the term. Broad inclusion and exclusion criteria of the search method were set to both include documents defining and categorizing natural resources as well as documents concerning their criticality. Figure 1 presents the codes concerning definitions of natural resources in the reviewed documents, gathered from 38 of the 105 reviewed documents. They could be split up into three main themes. One related definitions of natural resources to the physical environment. For example, they focused on biophysical processes of nature or the finiteness of stocks. A larger group of codes described natural resources as a dynamic concept, or even a social construct, dependent on its value in relation to human needs and wants. This view, namely, that "resources become" instead of that "resources are", was already elaborately described in an industrious volume by E. W. Zimmermann in 1951 [14]. A more recent example of this view was given by Cutter and Renwick [15], who argued that environmental cognition, "the mental process of making sense out of the environment that surrounds us", lies at the base of natural resources: "A resource does not exist without someone to use it. Resources are by their very nature human-centered. Different individuals or groups value resources differently". The largest group of codes described the intersection between these two views of natural resources, acknowledging both its provision by the natural environment and its value in relation to human activities. Andersen [1], for example, states that "natural resources exist independently of humans but are only identified as resources, and thus ascribed value, in relation to human activities".

There were 29 other codes related to defining natural resources which did not fit into the value driven and/or physical environment themes. Several of them describe the concept of natural capital, coined by ecological economists, as an addition to human capital and manufactured capital. It comprises natural resources and "the ecosystems that support and maintain the quality of land, air and water, and biodiversity" [16]. Another group of leftover codes pointed to the distinction in definitions between reserves and resources, exclusively for minerals, based on classification by the United States Geological Survey (USGS). Respectively, they represent "a mineral deposit that is currently economic (reserves) and another which may become economic in the future (resources)" [17]. The economic (and technological) feasibility indicates again, however indirectly, a human-value driven definition. The five text fragments in the middle of the diagram could be considered as the most comprehensive ones. They explain natural resources from a combined environmental and value-driven approach, while also adding an extra aspect. Le Billon [18], for example, stated that definitions of natural resources are often disputed due to contesting ideas of ownership over them. Dewulf et al. [19] (p. 5312) introduced the aspect that natural resources "may have a three-dimensional (volume) or a two-dimensional nature (surface)". Terrestrial and aquatic surfaces, according to them, are for example available for harvesting, production, or infrastructure. The other three documents in the middle of the diagram are [20–22].

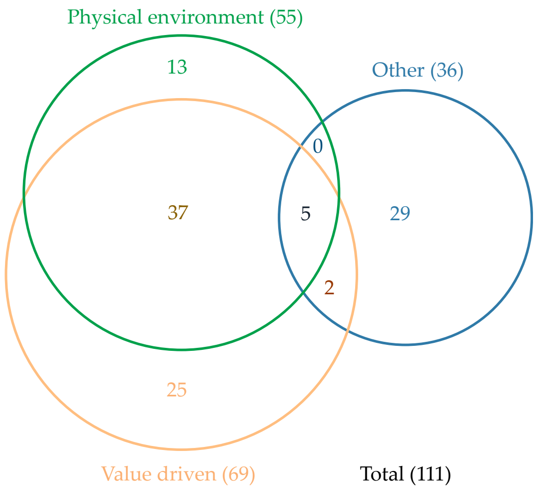

Figure 1. Venn diagram describing the amount of text fragments defining natural resources, coded into three themes. The total amount of text fragments (n = 111) were gathered from 38 of the 105 reviewed documents.

The coded text fragments make clear that both the physical environment as well as human valuation are important components of a definition of natural resources. Between all the reviewed definitions, the following one presents this duality the best in our opinion, found by Castleden [23] in a geography textbook by Daniels et al. [24]: "A substance in the physical environment that has value or usefulness to human beings and is economically feasible and socially acceptable to use". Castleden [23] thereby notes that natural resources' value can go beyond an economic one and include, for example, a role in human identity, relationships, and spirituality.

What constitutes natural resources and how they are classified is very closely related. Most often, they are classified according to their rate of regeneration: renewable and non-renewable resources. Renewable resources are defined as resources that regenerate on a human timescale (e.g., water, fish, and forests). Non-renewable resources do not regenerate over human timescales, for example, minerals. This simple subdivision is considered misleading, or even harmful by some scholars, as it leads to the belief that renewable resources will always stay available for human exploitation, regardless of their management [15]. Therefore, renewable resources can be further subdivided into unconditionally renewable resources, such as solar power, and conditionally renewable resources, such as wildlife. The unsustainable management of conditionally renewable resources can exhaust their regenerative capacity and make them non-renewable. Various terms are used to indicate these three subsequent classes of natural resources, which are presented in Table 1. From this simple table, an inconsistency in terminology is apparent between Cutter and Renwick [15] and Dewulf et al. [19]. While the former applies the term "flow resources" to conditionally renewable resources, the latter applies the same term for unconditionally renewable resources. To avoid confusion, we follow the terminology and classification of natural resources by Jowsey [25] in the rest of the paper.

Table 1. Natural resource classifications based on regenerative capacity.

Source	Non-Renewable	Renewable	
[25]	Non-renewable	Conditionally renewable	Unconditionally renewable
[19]	Exhaustible non-renewable	Exhaustible renewable	Inexhaustible renewable
[19]	Stock	Fund	Flow
[26,27]	Depletable	Critical zone	Continuous
[15]	Non-renewable/stock	Renewable/flow	Perpetual
Examples	Oil, genetic biodiversity, diamonds, metals, etc.	Fish stocks, soils, groundwater, timber, etc.	Solar, tidal, wind power, etc.

3.2. Overview of the Reviewed Publications on Criticality

An overview of the timing and location of the publications, which includes codes on the criticality of natural resources, is presented in Figure 2, as well as the subcodes/topics discussed in them. Their number amounts to 75 out of the total of 105 documents within the review. The first publication in this review dates from 1984 and focused on strategic minerals [3]. In the 1980s and 1990s, the topic was only sporadically present, and criticality was mainly related to strategy and defence. Although less dominant in the more recent literature, this continued to be a regularly discussed aspect of criticality. In the late 1990s and mid-2000s, a branch of publications focusing on critical natural capital appeared where environmental concerns were introduced into the criticality debate. From 2008 onwards, the topic started to gain more attention and grew notably up to a peak in 2015. It kept a strong presence in the literature until May 2017, when the gathering of publications for this review started. Since this new wave of interest, economic aspects of criticality have been introduced and have received most of the attention, next to technological, political, physical availability, strategic, and environmental aspects.

According to our interpretation, environmental concerns become present in the literature after the publication of the Brundtland Report [28] and the Rio Earth Summit in 1992 that both focused on sustainable development. The Kyoto Protocol was first published in 1998 [29] and the United Nations Millenium Decleration came out in 2000, which stressed the importance of sustainable development and protecting our common environment [30]. This suggests that these events, and increased global environmental awareness more generally, might have impacted the criticality discourse. Furthermore, the economic crisis of 2008 is likely linked to the increase in publications discussing the criticality concept more intensively. The European Commission report from 2010 on critical raw material [5] can also have further put the issue on the agenda, which links with the EU's action plan for the Circular Economy [31]. Since then, more weight has been placed on economic as well as technological concerns over the earlier defence and environmental concerns. Nonetheless, the topic of criticality in relation to the environment has not disappeared completely from the debate. The UN's 2030 Agenda for Sustainable Development came out in 2015 [32], which put a strong emphasis on environmental issues, further raising awareness on their importance in the global community.

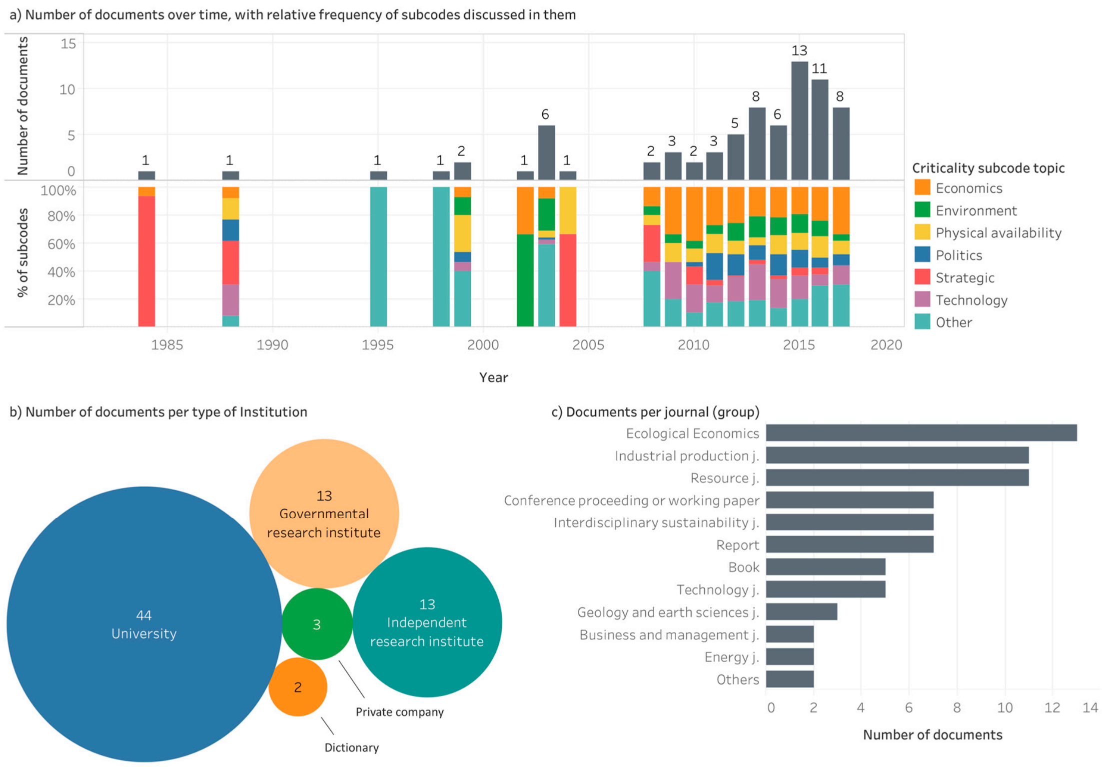

Figure 2. Overview of the publications included in the review on criticality of natural resources (n = 75): (**a**) number of publications over time, with indication on the number of subcodes per criticality aspect; (**b**) number of publications per type of organization of first author; (**c**) number of publications per type of journal (j. = journals, several grouped together from similar disciplines, see Appendix E for included journals).

Based on the location of the first author, 60% of the 75 publications were published by residents of the United Kingdom, Germany, or the United States. Additionally, publications from the Netherlands, Italy, and Canada together accounted for another 21%. The remaining publications were all produced in Western countries with the exception of two from Asia (i.e., [33,34]). Authors from the United Kingdom were the first ones to enter the debate alongside their Canadian colleagues until 2000. Dutch scientists joined after 2000 and US scholars followed in 2004. We found publications from Germany since 2009. Researchers from Italy, represented solely through the European Commission's Joint Research Centre, joined the debate in 2014. The two Asian publications in our review were both published in 2015.

These findings might indicate that natural resource criticality is a primarily Western concept. However, the search was performed in English which excludes publications in other languages. In the gathered publications, Korean, Japanese, and Russian reports were mentioned among others [35,36]. Additionally, there were no signs of standpoints in the criticality discussion from the global south. This plausible over-representation of Western perspectives could influence the understanding of criticality of natural resources since other parts of the world are not considered to the same extent.

Analysing the first author's affiliation shows that 59% of the publications were developed at universities, 17% at governmental research institutes and agencies, 17% at independent research institutes, and 4% at private companies (Figure 2). This indicates that various layers of society consider the topic to be important. The range of academic journals and other publishing media that covered studies on the criticality of natural resources was also diverse. Journals concerning resources (e.g., Resources Policy) and industrial production (e.g., Journal of Cleaner Production) accounted each for 15% of the reviewed literature. Resource journals were used as publishing media from the start, while the topic only started to appear, although frequently, in industrial production journals after 2014. Reports, often by governmental or independent research institutions, encompass 9% of the reviewed materials from 2008 onwards. Technology journals contain 7% of publications from 2011 on. Articles in the Journal of Ecological Economics represent 17% of publications which were mainly published in the 1990s and 2000s. One reason for this high percentage was the CRITINC research project about critical natural capital that ended in 2003 with a special issue on the topic in the Journal of Ecological Economics [37]. Many of the identified journals grouped above are interdisciplinary. What stood out from this review of publication platforms was that, except for a couple of economics related publications, there were few publications originating from the social sciences.

3.3. Definitions of Criticality

According to a number of scholars, the adjectives “critical”, “strategic”, and “scarce” have not been differentiated clearly from each other and, therefore, have been used interchangeably [2,38,39]. The historical conceptualisation and use of the concept “strategic” for natural resources is described by Haglund [3]. In brief, the concept was coined shortly after World War I, when shortages of certain natural resources revealed the need for industrial capacity and input to win wars. From the 1930s onwards, the concept “critical” was introduced, initially, as a separate category but later aggregated into one concept “strategic and critical materials”, which was still in use in the 1980s [3]. Currently, the terms “critical” and “strategic” are used separately where “critical” refers to threats to national economies, while “strategic” relates almost exclusively to military and defence needs [5,39,40].

Despite being a highly debated topic, many of the reviewed publications point out the fact that there is currently no universally agreed upon standard definition of criticality concerning natural resources (e.g., [2,41]). The variation in terminology is attributed to the multiple applications of the concept in diverse contexts, such as time or spatial scales [42,43]. Some authors prefer not to have a common definition so that “criticality is a relative concept and the relevant dimensions can (and should) be defined by the user according to his/her particular needs” [44] (p. 728). Some of the publications in this review did present a definition of criticality in relation to natural resources, shown in the Table 2 below.

Table 2. Verbatim definitions of the concept “critical” related to natural resources from the review in chronological order.

nr.	The Defined Concept	Definition	Source	Year of Publication
1	Strategic and critical materials	Strategic and critical materials are those materials required for essential uses in a war emergency, the procurement of which in adequate quantities, quality, and time is sufficiently uncertain for any reason to require prior provision for the supply thereof	[45]	1947
2	Strategic and critical materials	Those materials that (A) would be needed to supply the military, industrial, and essential civilian needs of the United States during a national emergency, and (B) are not found or produced in the United States in sufficient quantities to meet such need	[46]	1979
3	Critical natural capital	Vital parts of the environment that contribute to life support systems, biodiversity and other necessary functions denoted as ‘keystone species’ and ‘keystone processes’	[47]	1993
4	Critical natural capital	Ecological assets that are essential to well-being or survival	[48]	1993

Table 2. *Cont.*

nr.	The Defined Concept	Definition	Source	Year of Publication
5	Critical natural capital	Critical natural capital consists of assets, stock levels or quality levels that are: 1. Highly valued; and either 2. Essential to human health, or 3. Essential to the efficient functioning of life support systems, or 4. Irreplaceable or unsubstitutable for all practical purposes (e.g., because of antiquity, complexity, specialisation, location)	[49]	1994
6	Critical natural capital	Critical elements of the capital stock should be: 1. Essential to human health, but should also reflect the need for ecosystem health; 2. Essential to the efficient functioning of life support systems; 3. Irreplaceable or unsubstitutable for all practical purposes 4. In addition, irreversibility of environmental processes or stock changes has implications for intergenerational equity	[4] modified from [49]	1994
7	Critical natural capital	That part of the natural environment which performs important and irreplaceable functions	[21]	2003
8	Critical natural capital	That set of environmental resources which performs important environmental functions and for which no substitutes in terms of human, manufactured or other natural capital currently exist	[37] through [50]	2003
9	Critical natural capital	Natural capital which is responsible for important environmental functions and which cannot be substituted in the provision of these functions by manufactured capital	[37]	2003
10	Critical natural capital	Natural capital that is not substitutable by any other form of capital	[50]	2003
11	Critical natural capital, based on an anthropocentric perspective	The ecosystem services which are most important to our survival and well-being and cannot be substituted (focused mainly on production and information functions of natural ecosystems)	[50]	2003
12	Critical natural capital, based on an ecocentric perspective	The ecosystems which are most important to maintain environmental health/integrity (focused mainly on maintenance of regulation and habitat functions)	[50]	2003
13	Critical materials	Those [materials] for which a threat to supply from abroad could involve harm to the nation's economy	[39]	2008
14	Raw material criticality	To qualify as critical, a raw material must face high risks with regard to access to it, i.e., high supply risks or high environmental risks, and be of high economic importance. In such a case, the likelihood that impediments to access occur is relatively high and impacts for the whole EU economy would be relatively significant	[5] also referred to by [2,40]	2010
15	Raw material criticality (in the context of the general risk matrix)	In this context, raw material criticality can be interpreted as the systemic risk of damages to an economy due to disturbances in raw material supply	[51]	2012
16	Strategic or critical materials	If their supply is concentrated in one country or could be restricted by a few corporate interests, and because they are important economically or for national security	[52]	2012
17	Criticality of metals	The extent of current and future risks associated with a certain metal	[53]	2013

Table 2. *Cont.*

nr.	The Defined Concept	Definition	Source	Year of Publication
18	Criticality of metals	The quality, state or degree of being of the highest importance	[17,54]	2013, 2014
19	Criticality	The combination of the potential for supply disruption and the exposure of a system of interest to that disruption	[55]	2014
20	Criticality	The term 'criticality' describes an evaluation of the holistic importance of a resource, which can be interpreted as an assessment of the risks connected with resource production, use and end-of-life	[56] through [57]	2014
21	Criticality	A dynamic, multidimensional characteristic of materials. In other words, criticality in its meaning of "state of being critical" can refer to something as being vital, absolutely essential as well as to something that is verging on the state of emergency	[33]	2015
22	Criticality of ecosystem services	The criticality of ecosystem services depends on (i) the essential role of these services for human existence and well-being, (ii) the non-substitutability of the services with regard to their unique contribution to human well-being, and (iii) the risk of the services becoming irreversibly extinct if the natural capital that provides them is degraded beyond critical thresholds.	[58]	2015
23	Criticality of a raw material	A measure of the (economic) risk arising from its utilisation (incl. production, use, and end-of-life) for a specific consumer over a certain period	[59]	2017

The definitions found in the literature (Table 2) can be compared with the general definition of the term critical by Oxford English Dictionary Online [60] describing the terms' use and understanding in the everyday language: "Of the nature of, or constituting, a crisis: (a) Of decisive importance in relation to the issue. spec. [...], (b) Involving suspense or grave fear as to the issue; attended with uncertainty or risk". Many of the definitions in Table 2 describe criticality with respect to natural capital and raw materials or metals. Only two definitions, by Roelich et al. [55] and Helbig et al. [57], take a general stand or refer to resources explicitly. Further, many of the definitions seem to be derived from assessments of criticality and its specific methods, which has been noted before by Graedel and Nassar [54].

The various definitions we identified included keywords such as: risk (or threat, emergency), importance (supplemented by vital, essential), and, less commonly, unsubstitutable or irreplaceable. According to Frenzel et al. [59], many authors are not aware of the "true meaning of risk" and its fundamental links to criticality, leading to conceptual and methodological issues in research on critical natural resources. Correspondingly, de Groot et al. [50] argue that threat related to a resource should be discussed alongside the importance of a resource in the conceptualisation of critical natural resources. Concerning the importance of natural resources, de Groot et al. [50] claim that certain functions of natural resources are important "to the maintenance of the natural capital itself (especially the regulation and habitat functions)", while other functions of natural resources are "of direct benefit to human society" [50] (p. 190). Mancini et al. [44] developed a prioritization scheme of needs that resources fulfil, namely, the relative importance of their functions, adapted from the psychologist Maslow's pyramid of human needs (Figure 3). Unsubstitutable resources can be found at the base of the pyramid, described by Armstrong as "indispensable supports for the most basic functionings, and [...] vital supports for anyone's life" [22] (p. 15). Examples have been provided by [17], who are researchers mainly focused on minerals and metals. They [17] single out nitrogen, phosphate, and potash as the only minerals essential to life itself and, thus, unsubstitutable. They argue that all other minerals are substitutable because "it is the need or desire for the products that generates a demand for minerals, rather than demand for the mineral itself. As a result, there is always the possibility of finding an alternative material to provide the required functionality" [17] (p. 1). Next to minerals, [50] also give renewable resources, like clean air or fertile soils, as examples of unsubstitutable resources belonging in the base of the pyramid. Accordingly, they add to [17] that, although many functions of natural resources can be replaced by human inventions, it might be undesirable because it "is often technically difficult and usually imperfect, it is often socially undesirable and economically not very sensible" [50] (p. 197).

Several other aspects important to the definition of criticality for natural resources were brought up by our review. According to [50], inherent to the "importance" part of criticality is the question: important for whom? In general, most literature provides the answer that it is critical or important to (a certain part of) human society. In addition to that, some authors mention nonanthropocentric perspectives that consider parts of the natural environment as resources or even critical resources to other species than humans [23,50]. Within the dominant anthropocentric perspective, the criticality concept is guided by different interest groups such as, critical to: global human society (or humanity) [61], a region [35], a country [62], a corporation [63], an economic or industrial sector [64], or a specific product or technology [65]. This is one of the reasons why definitions and criticality assessments are considered context dependent by many authors, as mentioned earlier.

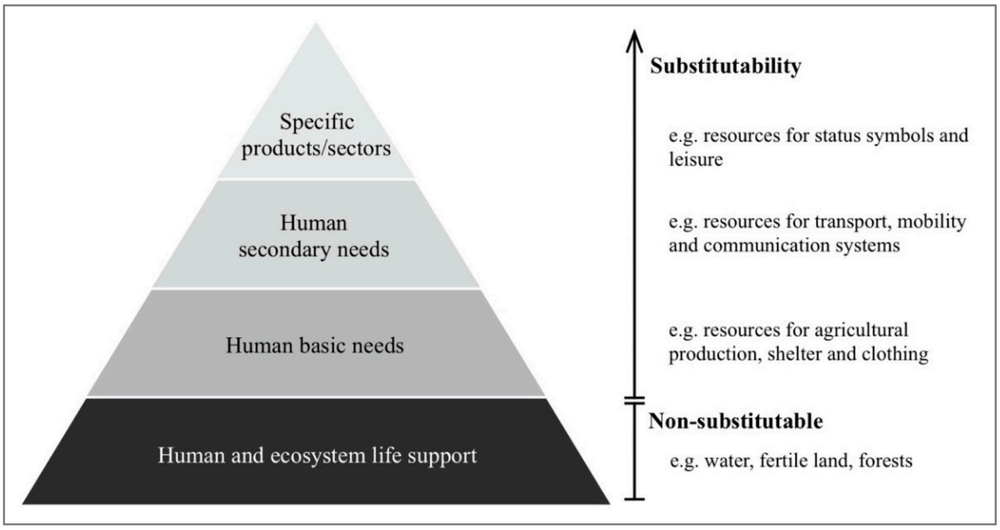

Figure 3. Prioritization of natural resource needs adapted from Mancini et al. [44].

A second aspect raised in some of the reviewed documents was the need to interpret the criticality of natural resources as dynamic, as it is not an inherent property of a resource [1,54]. Rather, the "state of being critical" [33] will evolve over time, for example, due to technological innovations, geopolitical changes, or climate change. Lastly, some articles discuss the importance of assessing the criticality of a certain natural resource relative to other ones (or to other interest groups or through time), as opposed to selecting an arbitrary threshold to divide critical and noncritical resources, e.g., [66].

3.4. Aspects of Criticality

As introduced in Figure 2, the concept of criticality contains different aspects captured by the subcodes. There were 773 in total, with the majority of the codes (22%) related to economic aspects of criticality. Technical aspects were second in line (15% of codes), physical availability as well as environmental aspects each accounted for 11%, political aspects of criticality were covered by 10% of the codes, and strategic aspects by 6%. Finally, sociohuman aspects and holistic approaches to criticality accounted for the rest (4% of the codes).

Thus, economic criticality concerns were most frequently discussed. Two of the main topics under economic aspects were risks of supply disruption and the ensuing economic consequences. The latter was also referred to as economic importance or vulnerability. Economic characteristics of natural resources mentioned as part of one or both of these topics included, for example: current and future supply and demand trends [7,40,63], price increases and volatility [39], competing demands [64], sensitivity of the relevant value chains [67], and consumption level [36]. Frenzel et al. [59] (p. 2), state that "most criticality assessments focus exclusively on economic aspects in their practical implementation". We would argue that this economic inclination is at the expense of other values and functions of the natural resources at risk. An underlying assumption seems to be that as long as economic interests are ensured, societal well-being will also be achieved.

Regarding technological aspects of criticality, continuous technological development changes the demand for natural resources, for example, emerging clean energy technologies which require rare earth metals and new bio-based materials that need algae [42,68]. A frequently mentioned aspect of these technological demand dynamics is the availability and performance of substitutes (e.g., [7]). Yet, as mentioned earlier, [17,22,50] counter these concerns by stating that only resources that perform life and ecosystem support functions are nonsubstitutable, represented in the base layer of Mancini et al.'s [44] prioritization pyramid of resource needs (Figure 3). Furthermore, technological development can enhance the efficiency of natural resource use and, thereby, reduce their criticality, for example, increased agricultural yield or extraction potential [69]. Recycling is a major topic related to this, complemented by the possibilities of reduction, reuse, and recovery [33]. The literature on this aspect was oriented towards non-renewables in industry. Yet, this argument could also apply to renewable resources. We recognise that technology, with its influence on both demand and supply, is closely interconnected with economic aspects. In general, innovation is seen as important to reduce the criticality of resources.

Physical availability or scarcity of natural resources is mentioned often in the criticality debate (11%). For non-renewable resources, its reserves are often compared to annual consumption or production rates, resulting in its remaining lifetime or depletion time. In general, many authors claim that the extent of natural resource stocks is less important to criticality than accessibility, which is rather defined by geopolitical and socioeconomic conditions [70–72]. This is partly due to uncertainties in reserve estimates and because criticality is often analysed on a shorter timescale than the depletion time of the resources being considered [5,55,73]. However, [74] showed that decreasing ore grades globally have required increasing amounts of energy for extraction. This trend is generally expected to continue with the discovery of new reserves [75]. Still, there is uncertainty about projected resource availability and the energy needed for extraction because of imprecise or lacking data and technological advances in prospecting, mining, recycling, and energy efficiency [75].

When considering renewable energy resources, innovation and transformation to a renewable energy system requires many non-renewable, mined resources [76]. Hence, the physical availability of renewable and non-renewable resource stocks is closely linked. The importance of physical availability has mainly been debated in relation to non-renewable and energy resources. However, when considering conditionally renewable resources, the necessity to maintain a certain level of resource stock for it to be able to renew itself and provide life and ecosystem support functions is emphasized [4]. We argue that more emphasis should be placed on the biophysical reality of renewable and non-renewable stocks for criticality considerations as compared to the economic concerns over stocks, such as yearly production rates.

When considering environmental aspects of criticality, the main topics discussed are the environmental side-effects of natural resource extraction and production on human health, ecosystems and their biodiversity, or the climate [77]. Some argue that good environmental standards and regulations in the resource's country of origin could lower the risk for supply disruption and, consequently, lower the criticality of the resource [5,65,72]. However, [78] (p. 587), interpreted the European Commission's [5] report differently. They believe the resource's criticality will increase with “stricter environmental regulation in an exporting country impairing imports of a resource type”. Most authors refer to environmental impacts and regulations without exactly stating how they might impact the criticality of the resource. Lastly, some publications also mention that the degradation of conditionally renewable resources can cause them to become critical, namely, when the ecological carrying capacity is exceeded and the resources lose their ability to renew themselves or perform their regulatory functions [44,78].

Another clear theme within natural resource criticality is political concerns. The largest concern is the low quality of governance or political instability in the supplying countries, in combination with the high geographical concentrations of resources in those countries [71]. Schillebeeckx [79] calls this situation “politically scarce”, where higher possibilities for political or social unrest might disrupt the supply of the resource. Bedder [6] is one of the few who mention corporate concentration as well as country concentration that can increase criticality due to oligopolistic market imbalances. Consequently, net import reliance and trade relationships can significantly impact the criticality of a resource: export restrictions and quotas in supplying countries increase the criticality, while trade agreements lower criticality for importing countries [7,8]. This way of comprehending export quota and trade agreements indicates to us that the concept of criticality is mainly used by and applied to importing, industrialized, Western countries. Export quota would protect the exporting country from losing access to its own critical natural resources and are thus only considered negative for countries that rely heavily on imports.

Further, [50] consider criticality evaluations a “political process” and others agree that the criticality of natural resources is influenced by the “prevailing political vision”, as the concept is largely used in governmental and consulting reports with the purpose of informing decision-making [33,36,80]. Our review (Figure 2) shows that the discussion is now more balanced by numerous scientific publications critiquing and contributing to the concept. Nonetheless, we can argue that the main interest is still political and that information is gathered to inform decision-making. Additionally, we would argue that the dominance of the initial defence aspects and the current economic inclination around the concept are an artefact of its political roots.

Strategic concerns of critical natural resources are closely related to political aspects and power over resources. Currently, “strategy” is not a dominant aspect of the criticality discourse (Figure 2). Most authors, almost exclusively, relate “strategic” to military and defence needs, as part of an overall criticality concept [5,39,40]. Now, strategic concerns are also attributed to another interest group than governments: namely, businesses [43]. The term “strategic”, as well as “critical”, has gone through a substantial expansion and transition over time. Haglund [3] explains that this is common for political concepts due to changing societal conditions and contested interpretations of the concept and, thus, does not consider it useful to define it. Despite the tendency of political concepts to change their meaning over time, we suggest authors clearly define what they mean by the term “critical natural resources”. Without proper definitions and conceptualisations in a majority of the reviewed publications, it is difficult to compare the use of the concept, even more so due to its multidisciplinary character. Only through discussions and debate of these multidisciplinary concepts can we deepen our understanding of the problems we are trying to comprehend and continue to build up (and upon) scientific knowledge from a collaboratively created body of literature [11].

The final two identified aspects of criticality are infrequently mentioned: sociohuman aspects and a holistic or integrated view. Regarding sociohuman aspects, some publications make a link between criticality and inadequate social conditions during extraction of resources and related regulations, such as human rights violations, resource conflicts, illicit trade, and precarious working conditions [44]. We discovered an inconsistency and ambiguity in the literature on whether regulations to protect employees, local inhabitants, and the environment from negative impacts of extraction processes increase or decrease the criticality of that resource (e.g., [8] vs. [81]). The inclusion of social and environmental regulation into evaluations of criticality shows an interest in broadening the debate from purely economic interests towards including social and environmental concerns.

Furthermore, only a handful of publications mention the sociocultural value of natural resources (e.g., [21]). The publications acknowledge that resources have important economic, life-support, and ecological functions. However, they do not recognise their immaterial sociocultural functions, such as physical and mental health, education, identity (heritage value), freedom, and spiritual values, that increase the general well-being of human society [21].

Despite the dominant economic and geopolitical interpretations of resource criticality, the above overview and several of the publications in the review demonstrate that criticality is determined by an interaction of many factors. They include economic, technological, physical availability, environmental, political, strategic, and social aspects of the concept [4,44,50,57,80]. Therefore, some authors plea for a more challenging, interdisciplinary approach to explore sustainable options for natural resource use, acknowledging and comprehending the dynamic interplay between all these aspects [21,44,82]. Nevertheless, [2] warn for the paradox of comprehensiveness versus accuracy. We do not agree with claims made by, for example, [3,81], that a broad aggregate concept of criticality would make it practically useless or inaccurate. Risks are everywhere. Only accounting for certain aspects of risks to natural resources while leaving other aspects behind is a distortion of the information that serves as a basis upon which natural resource policies are built. A clear specification is needed of which functions of a natural resource are threatened and in what way (e.g., economic, sociocultural or life, and ecosystem support functions). Mancini et al.'s [44] ranking of importance between the different functions of natural resources (Figure 3) is useful for that purpose.

Thus, overall, we found a dominance of the economic aspect of criticality. Furthermore, we identified an under-representation of the importance of physical availability, uncertainty on how to incorporate environmental and social impacts, as well as a dominant Western perspective. The political roots and goals of the concept steered its conceptualisations towards defence and, later, economic aspects. We suggest that there is a need for a holistic, integrated concept of criticality for natural resources, open to different value orientations regarding natural resources to balance the uncovered perspectives. Possible methodological limits in reaching these findings are discussed in Section 3.5 before reaching our conclusions.

3.5. Criticality Assessments

It is not our goal to give a full review of natural resource criticality assessment methodologies, especially considering the number of existing reviews of the topic (e.g., [59]). However, an extensive analysis of the criticality discourse cannot be done without touching upon them, since they are the main way of application and communication of the concept.

3.5.1. The Tools of Criticality Assessments

Several types of tools exist for quantifying and communicating natural resource criticality. They most often include detailed time series and scenario analyses per natural resource or hierarchical risk ranking based on indicator selection and aggregation [62]. The criticality matrix is most often applied, locating various resources as dots between two dimensions or axes of basic risk theory: (1) the probability of a disruption in the resource supply, often termed "supply risk" and (2) the impact caused by such a constraint, termed "vulnerability" [72,83]. The overall risk is the product of these two dimensions, creating hyperbolic contours of constant criticality within the plot [40]. However, these axes are often modified to the extent of losing the connection with risk theory, for example, by changing the terminology and indicators of the axes or by adding or omitting an axis [50,57,59]. Thus, when selecting indicators for a criticality matrix, attention and strictness are required to avoid using vague or ambiguous terminology of the axes.

Furthermore, the more methodologically oriented publications in the review showed that criticality assessments need to be directed towards a specific interest group [66] and timescale [81]. They should also be relative to other contexts, such as other resources, spatial, or timescales [66,84]. Additionally, periodic re-evaluations are required when a static tool is used to assess the dynamic and evolving state of resources [67,82]. It is important to highlight that these considerations are exactly the same ones as mentioned before as important parts of the definition of criticality for natural resources.

3.5.2. A Predominance of Non-Renewable Resources in Criticality Assessments

The scope of natural resources considered in criticality assessments is mainly limited to minerals or, even more narrowly, to metals [5,36,67,77,85]. According to [36] (p. 7620), "supply risks of fossil fuels and their impacts on economies have been examined for decades, only in recent years have studies appeared that evaluate the criticality of a broad set of nonfuel minerals". Also, in Table 2, 9 of the 24 criticality definitions relate specifically to materials (i.e., minerals and metals). Graedel and Reck [66] (p. 696), contend that it is desirable for evaluations to be "broad in terms of elements addressed". A plausible explanation is that the language used to describe shortages in renewable resources has been expanding to other concepts than solely criticality. Many conditionally renewable resources can become scarce or critical if their management is unsustainable. Therefore, concepts linking to sustainability thinking—such as sustainable yield, used in [86], sustainable natural resource management, used in [87], and resource governance, used in [88,89]—could add to the debate on criticality of renewable resources without being captured in our systematic literature review.

We would argue that there are possibilities to broaden the scope of natural resources discussed in criticality debates and assessments by explicitly including renewable resources. This has been shown in assessments by Chapman et al. [35] of natural rubber, pulpwood, and soft sawnwood for the European Commission's report [73] and by Sonderegger et al. [90] of water. Additionally, de Groot et al. [50] developed a framework to assess the criticality of renewable resources, although no applications of it were found. Generally, these approaches correspond to the more common criticality matrices for minerals based on risk theory, with the modification or addition of some indicators. The four abovementioned research documents show that a holistic approach to criticality evaluations of natural resources is possible and that it is not necessary to separate renewables and non-renewables or to do so in their terminology: natural capital and materials, such as minerals and metals, as in Table 2.

Moreover, we argue for the need to widen the scope of natural resources included in criticality assessments. Renewable resources perform the main functions necessary for basic life and ecosystem support, located at the base of Mancini et al.'s [44] resource prioritization pyramid for human needs (Figure 3). Klinglmair et al. [78] (p. 586) agree that "impacts on the carrying capacity of ecosystems and their intrinsic capability of renewal may lead to impact on human needs and life greater than shortage in, e.g., mineral resources". The relative level of criticality can only be established per resource and compared among them when a criticality analysis incorporates a wide array of natural resources. Most of the pyramid's basic functions (Figure 3) are not valued within economic markets. Consequently, even if renewable natural resources are incorporated into the mainstream criticality assessments, the natural resources most critical to humanity will probably be overlooked as current analyses are mainly based on economic arguments and indicators.

Overall, we need to be aware that criticality assessments have communicative power and can be highly influential when it comes to decision-making, even when the assessment is executed without a rigorous conceptual and theoretical foundation. In order to design policies that ensure sustainable management of natural resources, balanced information is needed. Therefore, we propose that criticality assessments should include two things: first, a wide range of natural resources, including renewables resources along with the traditional non-renewables; second, an evaluation of resource importance based on human needs (e.g., with Mancini et al.'s [44] resource prioritization pyramid (Figure 3)). That includes sociocultural values and life and ecosystem support functions in addition to the standard economic arguments and indicators. If these two conditions are met, we expect other resources, such as clean water, clean air, forests, fertile soil, etc., to have a much higher criticality level relative to certain metals and rare earth minerals that are now commonly considered critical. Consequently, these resources might gain more attention in policy circles.

We consider it appropriate to define a concept before applying it in assessments and methodologies. In the literature we reviewed, only a handful of publications did so, despite the widespread use of resource criticality assessments (Table 2). As a consequence, many of the existing definitions are derived from the assessment methods, instead of the other way around. We argue that a holistic definition of criticality for natural resources, aligned with risk theory, might reduce inconsistencies and increase comparability among assessment methods. This could provide a common basis for balanced information to decision-makers while opening up to various value orientations for natural resources.

3.6. Proposal for a Holistic Definition

As mentioned in the beginning of this paper, definitions of critical natural resources were presented within academic disciplines that only engaged in cooperation or debate to a limited extent, for example, the clear division between definitions of critical materials and critical natural capital (Table 2). Nonetheless, the information gathered on a definition of "critical" for natural resources indicates common ideas of the concept: both an aspect of uncertainty or threat, as well as importance. These keywords relate directly to the two dimensions of risk according to standard risk theory and analyses [83]. Although this might be an artefact of creating definitions based on the tools used for criticality assessments, risk theory brings fundamental understanding to the concept of criticality. Therefore, we see it fitting to align our definition with risk theory. Simultaneously, risk analyses frameworks provide a foundation for criticality assessments.

We propose the following, generally applicable, definition of criticality for natural resources, which is an adaptation of the Oxford Dictionary [60] definition:

Criticality is a relative and dynamic state of a natural resource:

(a) of decisive importance, ranked according to a hierarchy of human needs, in relation to the issue or interest group specified, and
(b) attended with uncertainty or a threat.

We argue that this definition is aligned with risk theory [83] because of its two components: importance of the function of this resource, linked to the severity of outcomes of specified objectives, and threat or uncertainty. Moreover, the definition accounts for a specific interest group, timescale, and the dynamic and relative character of criticality, all previously mentioned as important for definitions and assessments of criticality. By relative, we mean a resource cannot be critical in itself, but that additional perspectives need to be addressed. For example, a resource should be relative to itself through time or to other resources at the same time. Local perspectives can be compared to the global scale. Criticality could also be relative from one place to another or from the perspective of one population group to another.

This definition allows for and encourages a holistic understanding of natural resource criticality. Firstly, by allowing for the perspectives, values, and assessments from any kind of interest group (i.e., also global, local, and non-Western perspectives). Secondly, it can be applied to renewable as well as non-renewable resources, preferably to both at the same time (i.e., within a wide array of natural resources). Lastly, we propose that the resource's importance should be explicitly ranked according to a hierarchy of human needs (e.g., Mancini et al.'s [44] resource prioritization (Figure 3)). Thereby, we suggest that the criticality of a resource increases when moving down the pyramid to basic human needs. Another less instrumental way of establishing a hierarchy of resource needs could be based on relational value frameworks, as advocated by Castleden [18]. Both allow to lessen the dominance of economic interests over other sociocultural and life-support values of natural resources. That way, the proposed definition of criticality could ensure more balanced information in criticality assessments and policy recommendations. We invite those who are interested to comment, contest, and develop our proposed definition.

Before summarizing our conclusions, we would like to point the reader to some of the recent literature within and outside of our review that does approach critical natural resources from the more neglected perspectives. Criticality of renewables have been assessed for water [90] and soils [91]. Moreover, this latter reference provides a more global perspective by teaming up authors from Kenya, the United States, Ghana, the United Kingdom, Argentina, Italy, Germany, and Denmark. Chiesura and de Groot [21] introduced critical sociocultural functions of renewable resources. Even though political science, psychology, sociology, ethics, and other social sciences are more and more present in natural resource research, we have not encountered any thorough social science scholarship that engages with concepts of resource criticality.

Lastly, there are some limitations in our methodology and analysis which carry forward into the presented understanding of the concept of "critical natural resources". First, the systematic literature search was limited to English documents. This could partly explain the lack of non-Western publication, for example, from Africa, Asia, and Latin America. Hamel [92] states that 75% of international scientific periodical literature in social sciences and 90% in natural sciences is published in English. Consequently, we can assume to have captured the international scientific literature while probably missing out on non-English national scientific journals, books, and reports. Another disadvantage of our search strategy is that grey literature, such as books and reports, are more difficult to systematically discover because they are not gathered in large publicly available databases like scientific journal articles are. This means that in our data, scientific perspectives probably prevail over practitioners' knowledge. Further, in our search string (see Appendix A), we accounted for the terms "resource", "material", and "natural capital" in relation to criticality. There are more terms describing natural resources that we did not include, such as "environmental assets" and "ecosystem services". From our preparatory literature research, these terms did not occur frequently in combination with criticality. Additionally, they are explicitly part of definitions of natural capital [93]. Likewise, we assumed other terms for "natural resources" were largely covered by the included terms.

4. Conclusions

The discourse around critical natural resources ascribes certain resources to be more critical than others and provides management guidance for them. By doing so, the discourse has a large influence on decision-making regarding natural resources. Diverging understandings of criticality for natural resources consequently lead to different policy outputs. Therefore, we set out to analyse the main understandings and underlying assumptions captured in the criticality debate on natural resources. By systematically mapping out the discourse, we did not come upon one generally accepted definition of the concept. Aspects commonly brought up as contributing to resource criticality were: economic, technological, physical availability, environmental, political, and, to a minor extent, sociohuman and holistic perspectives.

We identified several trends in the interpretation and use of the concept. First and foremost, economic concerns dominate the discourse on natural resource criticality at the expense of other values and functions, especially since the economic crisis of 2008. We argue for the need to balance out resource criticality considerations with more emphasis on the biophysical reality of natural resource stocks. Especially for those that provide nonsubstitutable life and ecosystem support functions. Sociocultural values of natural resources to human well-being should also be given more attention.

Secondly, published material about the topic comes mainly out of Western countries and, throughout our reading, we did not come across a standpoint on the topic from the Global South. Third, there is a clear distinction between the two main scientific branches that describe criticality, that is, ecologically versus industrially oriented disciplines. Moreover, social sciences, except for economics, are largely missing from the debate. Lastly, the majority of criticality studies solely focus on non-renewable resources, such as minerals and metals, without considering renewable resources. This could be the result of renewable resources and their criticality being discussed with different terminology not captured within this study. We, however, advocate for taking renewable resources further into account when discussing criticality and have questioned the usefulness of a distinct non/renewable split in the discourse. In sum, we addressed the need to broaden the scope of the criticality discourse to include more perspectives, scientific disciplines, and types of natural resources.

Based on this review, we developed a holistic definition of criticality for natural resources. We argue that the expansion of the criticality concept does not make it redundant. Rather, a holistic approach is necessary to provide decision-makers with neutral and balanced information and recommendations on natural resource management.

Further research possibilities include an analysis of non-English documents on the topic to address the main methodological limitation of this review. Secondly, it would be interesting to investigate how the development of the criticality concept for natural resources links to developments in sustainability thinking. Specifically, the hypothesis came up that there is a broader language to describe crisis situations for renewables than for non-renewables, which could have led to the over-representation of non-renewables in criticality assessments compared to renewables. Lastly, a streamlined methodology for criticality assessments could be developed based on the proposed definition of criticality for natural resources.

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Conflicts of Interest: The authors declare no conflict of interest.

Appendix A Literal Search Strings Applied to the Scientific Literature Databases

The developed search string for Web of Science:

("natural resource")*
AND (("critic" OR "strategic" OR "key") NEAR/20 ("resourc*" OR "material*" OR "natural capital"))*
AND (("defin" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties") NEAR/20 ("resourc*" OR "material*" OR "natural capital"))*

The developed search string for Scopus, approaching the previous syntax as much as possible:

KEY ("natural resource")*
AND TITLE-ABS-KEY ((("critic" OR "strategic" OR "key") PRE/20 ("resource*" OR "material*" OR "natural capital"))*
OR (("resource" OR "material*" OR "natural capital") PRE/20 ("critic*" OR "strategic" OR "key")))*
AND TITLE-ABS-KEY ((("defin" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties") PRE/20 ("resource*" OR "material*" OR "natural capital"))*
OR (("resource" OR "material*" OR "natural capital") PRE/20 ("defin*" OR "categor*" OR "classif*" OR "typology" OR "character*" OR "properties")))*

Appendix B

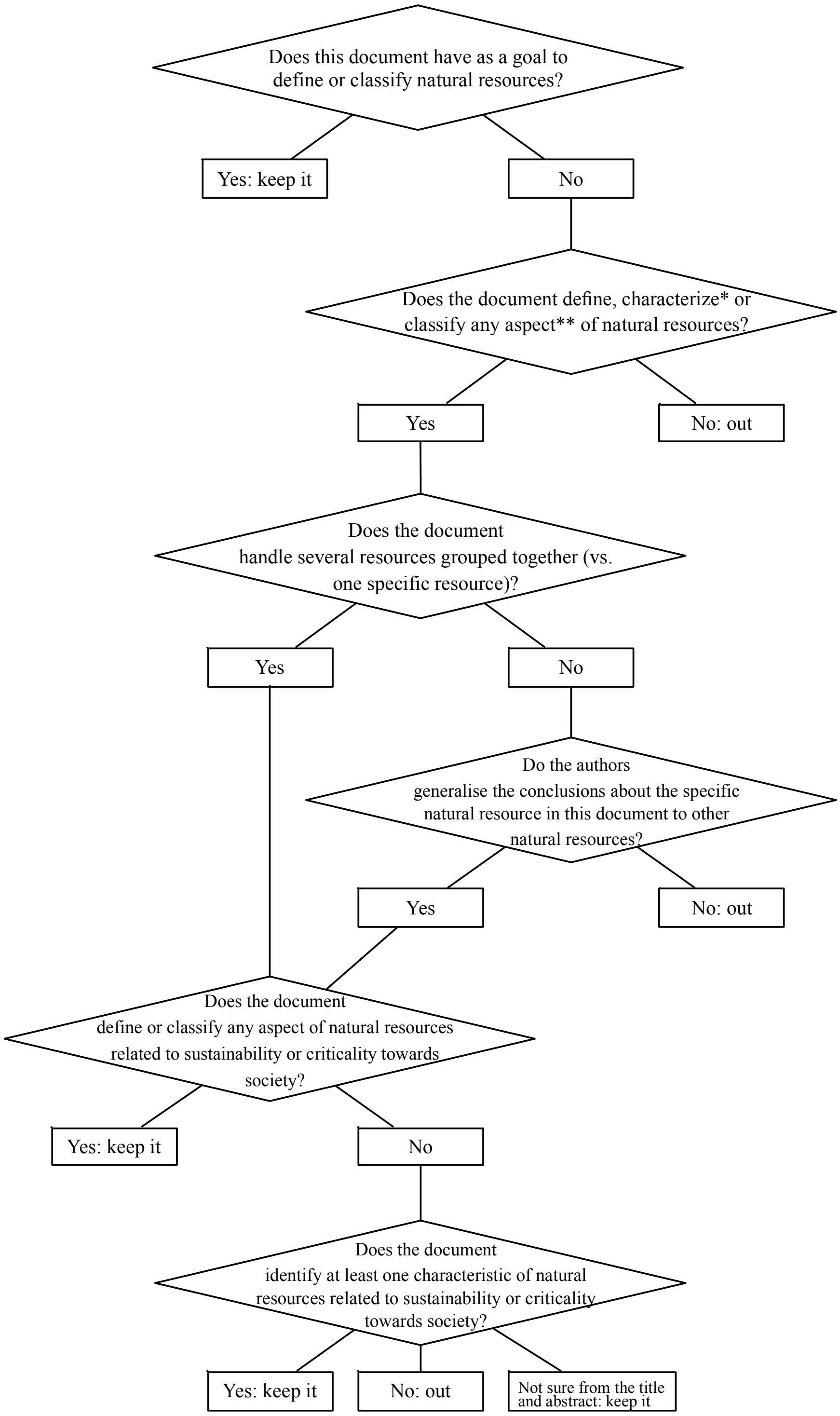

Figure A1. Inclusion and exclusion criteria for the selection of documents into the review. * with characterize, we mean identify characteristics or properties. ** any aspect of natural resources (e.g., resource use, management, production, extraction, impacts, etc.).

Appendix C

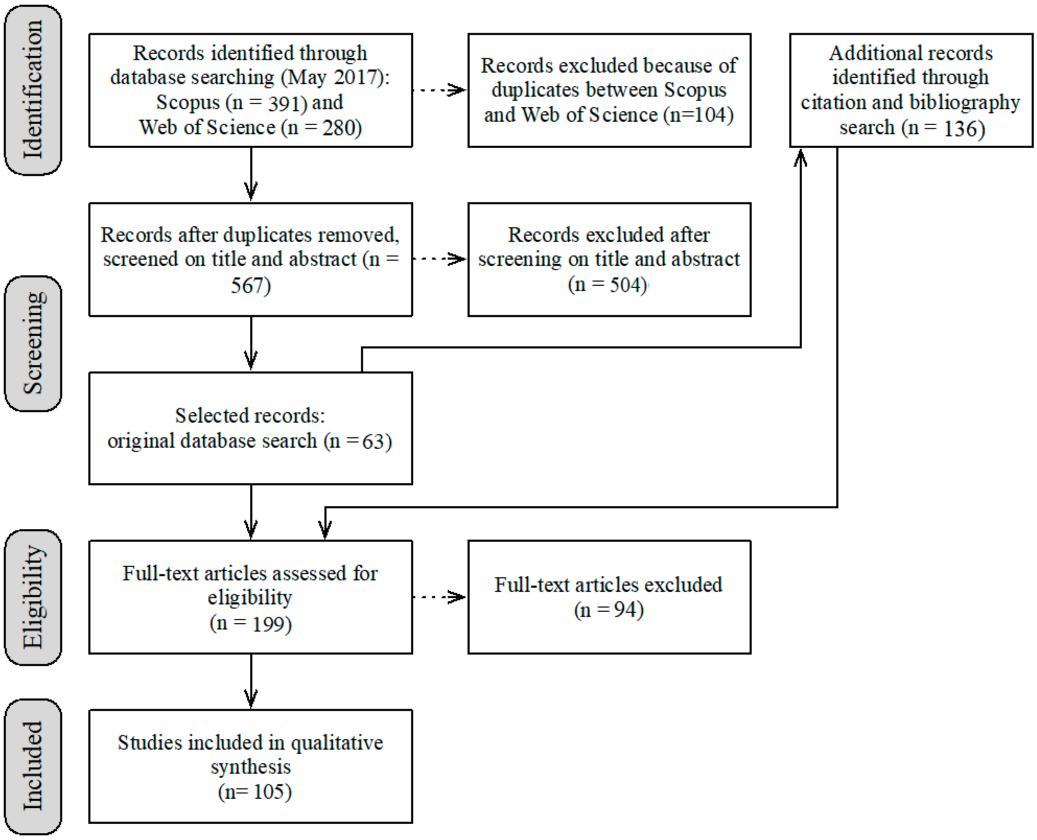

Figure A2. Flow diagram indicating the number of documents in each selection step of document gathering for the review.

Appendix D

Table A1. A list of all reviewed publications.

nr.	Authors	Year	Title	Journal
1	Achzet, B., and Helbig, C.	2013	How to evaluate raw material supply risks—an overview	Resources Policy
2	Andersen, A. D.	2012	Towards a new approach to natural resources and development: the role of learning, innovation and linkage dynamics	Int. J. Technological Learning, Innovation and Development
3	APS Panel on Public Affairs (POPA) & the Materials Research Society (MRS)	2011	Energy Critical Elements: Securing Materials for Emerging Technologies	Report
4	Armstrong, C.	2017	Justice and Natural Resources: An Egalitarian Theory	Book
5	Bach, V., Berger, M., Finogenova, N., and Finkbeiner, M.	2017	Assessing the Availability of Terrestrial Biotic Materials in Product Systems (BIRD)	Sustainability
6	Bach, V., Berger, M., Henssler, M., Kirchner, M., Leiser, S., Mohr, L., Rother, E., Ruhland, K., Schneider, L., Tikana, L., Volkhausen, W., Walachowicz, F., and Finkbeiner, M.	2016	Integrated method to assess resource efficiency—ESSENZ	Journal of Cleaner Production
7	Bedder, J.C.M.	2015	Classifying critical materials: a review of European approaches	Applied Earth Science

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
8	Bell, J.E., Autry, C.W., Mollenkopf, D.A., and Thornton, L.M.	2012	A Natural Resource Scarcity Typology: Theoretical Foundations and Strategic Implications for Supply Chain Management	Journal of Business Logistics
9	Blengini, G.A., Nuss, P., Dewulf, J., Nita, V., Peirò, L.T., Vidal-Legaz, B., Latunussa, C., Mancini, L., Blagoeva, D., Pennington, D., Pellegrini, M., Van Maercke, A., Solar, S., Grohol, M., and Ciupagea, C.	2017	EU methodology for critical raw materials assessment: Policy needs and proposed solutions for incremental improvements	Resources Policy
10	Brand, F.	2009	Critical natural capital revisited: Ecological resilience and sustainable development	Ecological Economics
11	Bridge, G.	2009	Material Worlds: Natural Resources, Resource Geography and the Material Economy	Geography Compass
12	Buchert, M., Schüler, D., and Bleher, D.	2009	Critical metals for future sustainable technologies and their recycling potential	Report
13	Buijs, B., and Sievers, H.	2011	Critical Thinking about Critical Minerals: Assessing risks related to resource security	Briefing or working paper
14	Buijs, B., Sievers, H., and Espinoza, L.A.T.	2012	Limits to the critical raw materials approach	Waste and Resource Management
15	Castleden, H.	2009	Rethinking Key Concepts: A precursor to rethinking environmental management	Environments Journal Volume
16	Chakhmouradian, A.R., Smith, M.P., and Kynicky, J.	2015	From "strategic" tungsten to "green" neodymium: A century of critical metals at a glance	Ore Geology Review
17	Chapman, A., Arendorf, J., Castella, T., Thompson, P., Willis, P., Espinoza, L.T., Klug, S., and Wichmann, E.	2013	Study on Critical Raw Materials at EU Level	Report
18	Chiesura, A., and de Groot, R.	2003	Critical natural capital: a sociocultural perspective	Ecological Economics
19	Ciacci, L., Nuss, P., Reck, B.K., Werner, T.T., and Graedel, T.E.	2016	Metal Criticality Determination for Australia, the US, and the Planet—Comparing 2008 and 2012 Results	Resources
20	Cimprich, A., Young, S.B., Helbig, C., Gemechu, E.D., Thorenz, A., Tuma, A., and Sonnemann, G.	2017	Extension of geopolitical supply risk methodology: Characterization model applied to conventional and electric vehicles	Journal of Cleaner Production
21	Collados, C., and Duane, T.P.	1999	Natural capital and quality of life: a model for evaluating the sustainability of alternative regional development paths	Ecological Economics
22	Cutter, S.L., and Renwick, W.H.	2004	Exploitation, conservation, preservation: a geographic perspective on natural resource use	book, publisher: John Wiley and Sons, USA
23	de Groot, R.S., Wilson, M.A., and Boumans, R.M.J	2002	A typology for the classification, description and valuation of ecosystem functions, goods and services	Ecological Economics
24	de Groot, R., Van der Perk, J., Chiesura, A., and van Vliet, A.	2003	Importance and threat as determining factors for criticality of natural capital	Ecological Economics
25	Deutsch, L., Folke, C., and Skånberg, C.	2003	The critical natural capital of ecosystem performance as insurance for human well-being	Ecological Economics
26	Dewulf, J., Benini, L., Mancini, L., Sala, S., Andrea, Blengini, G., Ardente, F., Recchioni, M., Maes, J., Pant, R., and Pennington, D.	2015	Rethinking the Area of Protection "Natural Resources" in Life Cycle Assessment	Environmental Science & Technology
27	Dewulf, J., Blengini, G.A., Pennington, D., Nussa, P., and Nassar, N.T.	2016	Criticality on the international scene: Quo vadis?	Resources Policy

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
28	Dewulf, J., Mancini, L., Blengini, G.A., Sala, S., Latunussa, C., and Pennington, D.	2015	Toward an Overall Analytical Framework for the Integrated Sustainability Assessment of the Production and Supply of Raw Materials and Primary Energy Carriers	Journal of Industrial Ecology
29	Drost, D., and Wang, R.	2015	Rare earth element criticality and sustainable management	Conference proceedings
30	Edwards, V., and Steins, N.	1999	A framework for analysing contextual factors in common pool resource research	Journal of Environmental Policy & Planning
31	Ekins, P.	2003	Identifying critical natural capital: Conclusions about critical natural capital	Ecological Economics
32	Ekins, P., Folke, C., and De Groot, R.	2003	Identifying critical natural capital (editorial)	Ecological Economics
33	Ekins, P., Simon, S., Deutsch, L., Folke, C., and De Groot, R.	2003	A framework for the practical application of the concepts of critical natural capital and strong sustainability	Ecological Economics
34	England, R.W:	1998	Should we pursue measurement of the natural capital stock?	Ecological Economics
35	EU Commission	2010	Critical raw materials for the EU: Report of the Ad-hoc Working Group on defining critical raw materials	Report
36	EU Commission	2014	Report on Critical Raw Materials for the EU: Report of the Ad hoc Working Group on defining critical raw materials	Report
37	Fischer-Kowalski, M., Krausmann, F., Giljum, S., Lutter, S., Mayer, A., Bringezu, S., Moriguchi, Y., Schütz, H., Schandl, H., and Weisz, H.	2011	Methodology and Indicators of Economy-wide Material Flow Accounting: State of the Art and Reliability Across Sources	Journal of Industrial Ecology
38	Folke, C., Hammer, M., Costanza, R., and Jansson, A.	1994	Investing in Natural Capital—Why, What, and How?	Book chapter in: Investing in Natural Capital—The Ecological Economics Approach to Sustainability
39	Frenzel, M., Kullik, J., Reuter, M.A., and Gutzmer, J.	2017	Raw material 'criticality'—sense or nonsense?	Journal of Physics D: Applied Physics
40	Gemechu, E.D., Helbig, C., Sonnemann, G., Thorenz, A. and Tuma, A.	2016	Import-based Indicator for the Geopolitical Supply Risk of Raw Materials in Life Cycle Sustainability Assessments	Journal of Industrial Ecology
41	George, G., Schillebeeckx, S.J.D., and Liak, T.L.	2015	The management of natural resources: an overview and research agenda	Academy of Management Journal
42	Glöser-Chahoud, S., Espinoza, L.T., Walz, R. and Faulstich, M.	2016	Taking the Step towards a More Dynamic View on Raw Material Criticality: An Indicator Based Analysis for Germany and Japan	resources
43	Glöser, S.	2012	Quantitative Analysis of the Criticality of Mineral and Metallic Raw Materials Based on a System Dynamics Approach	Conference proceedings
44	Glöser, S., Espinoza, L.T., Gandenberger, C., and Faulstich, M.	2015	Raw material criticality in the context of classical risk assessment	Resources Policy
45	Erdmann, L., and Graedel, T.E.	2011	Criticality of Non-Fuel Minerals: A Review of Major Approaches and Analyses	Environmental Science & Technology
46	Graedel, T.E., and Nassar, N.T.	2013	The criticality of metals: a perspective for geologists	Geological Society, London, Special Publications
47	Graedel, T.E., Gunn, G., and Espinoza, L.T.	2014	Metal resources, use and criticality	Book Chapter in: Critical Metals Handbook
48	Graedel, T.E., Barr, R., Chandler, C., Chase, T., Choi, J., Christoffersen, L., Friedlander, E., Henly, C., Jun, C., Nassar, N.T., Schechner, D., Warren, S., Yang, M., and Zhu, C.	2012	Methodology of Metal Criticality Determination	Environmental Science & Technology

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
49	Graedel, T.E., and Reck, B.K.	2015	Six Years of Criticality Assessments: What Have We Learned So Far?	Journal of Industrial Ecology
50	Graedel, T.E., Harper, E.M., Nassar, N.T., Nuss, P., and Reck, B.K.	2015	Criticality of metals and metalloids	Proceedings of the National Academy of Sciences
51	Habib, K., and Wenzel, H.	2016	Reviewing resource criticality assessment from a dynamic and technology specific perspective—Using the case of direct-drive wind turbines	Journal of Cleaner Production
52	Habib, K., Hamelin, L., Wenzel, H.	2016	A dynamic perspective of the geopolitical supply risk of metals	Journal of Cleaner Production
53	Haglund, D.G.	1984	Strategic minerals: A conceptual analysis	Resources Policy
54	Hallstedt, S.I., and Isacsson, O.	2017	Material criticality assessment in early phases of sustainable product development	Journal of Cleaner Production
55	Hanna, S., Folke, C., and Mäler, K.	1995	Property Rights and Environmental Resources	Book Chapter in: Property Rights and the Environment—Social and Ecological Issues
56	Hanna, S., Folke, C., and Mäler, K.	1996	Rights to Nature: Ecological, Economic, Cultural, and Political Principles of Institutions for the Environment	Book, publisher: Island Press
57	Helbig, C., Wietschel, L., Thorenz, A., and Tuma, A.	2016	How to evaluate raw material vulnerability—An overview	Resources Policy
58	Hennebel, T., Boon, N., Maes, S., and Lenz, M.	2015	Biotechnologies for critical raw material recovery from primary and secondary sources: R&D priorities and future perspectives	New Biotechnology
59	Jacobson, D.M., Turner, R.K., and Challis, A.A.L.	1988	A reassessment of the strategic materials question	Resources Policy
60	Jin, Y., Kim, J., and Guillaume, B.	2016	Review of critical material studies	Resources, Conservation and Recycling
61	Jowsey, E.	2007	A new basis for assessing the sustainability of natural resources	Energy
62	Jowsey, E., and Kellett, J.	1995	The comparative sustainability of resources	International Journal of Sustainable Development & World Ecology
63	Klinglmair, M., Sala, S., and Brandão, M.	2014	Assessing resource depletion in LCA: a review of methods and methodological issues	International Journal of Life Cycle Assessment
64	Knoeri, C., Wäger, P.A., Stamp, A., Althaus, H.J., and Weil, M.	2013	Towards a dynamic assessment of raw materials criticality: Linking agent-based demand—With material flow supply modelling approaches	Science of the Total Environment
65	Le Billon, P.	2014	Wars of Plunder: Conflicts, Profits and the Politics of Resources	Book
66	Lloyd, S., Lee, J., Clifton, A., Elghali, L., and France, C.	2012	Recommendations for assessing materials criticality	Waste and Resource Management
67	Lujala, P.	2003	Classification of natural resources	Unpublished manuscript, available at Researchgate
68	MacDonald, D.V., Hanley, N., and Moffatt, I.	1999	Applying the concept of natural capital criticality to regional resource management	Ecological Economics
69	Malinauskien, M., Kliopova, I., Slavickait, M., and Staniskis, J.K.	2016	Integrating resource criticality assessment into evaluation of cleaner production possibilities for increasing resource efficiency	Clean Technologies and Environmental Policy
70	Mancini, L., Sala, S., Recchioni, M., Benini, L., Goralczyk, M. and Pennington, D.	2015	Potential of life cycle assessment for supporting the management of critical raw materials	International Journal of Life Cycle Assessment
71	Mancini, L., Benini, L., and Sala, S.	2016	Characterization of raw materials based on supply risk indicators for Europe	International Journal of Life Cycle Assessment
72	National Research Council	2008	Minerals, Critical Minerals, and the U.S. Economy	Report

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
73	O'Neill, D.W.	2015	What Should Be Held Steady in a Steady-State Economy? Interpreting Daly's Definition at the National Level	Journal of Industrial Ecology
74	Oxford English Dictionary Online	2017	critical, adj.	Oxford English Dictionary Online
75	Oxford English Dictionary Online	2017	criticality, n.	Oxford English Dictionary Online
76	Oxford English Dictionary Online	2017	natural, adj. and adv.	Oxford English Dictionary Online
77	Oxford English Dictionary Online	2017	resource, n.	Oxford English Dictionary Online
78	Peck, D., Kandachar, P., and Tempelman, E.	2015	Critical materials from a product design perspective	Materials and Design
79	Pelenc, J., and Ballet, J.	2015	Strong sustainability, critical natural capital and the capability approach	Ecological Economics
80	Pessoa, A., and Silva, M.R.	2009	Environment based innovation: Policy questions	Finisterra
81	Gabriela-Cornelia, P.	2008	Evaluation method of natural resources sustainability	Bulletin of the University of Agricultural Sciences & Veterinary Medicine Cluj-Napoca. Agriculture
82	Pretty, J.	2003	Social Capital and the Collective Management of Resources	Science
83	Purnell, P., Dawson, D., Roelich, K.E., Steinberger, J.K., and Busch, J.	2013	Critical materials for infrastructure: local vs. global properties	Conference proceedings
84	Roelich, K., Dawson, D.A., Purnell, P., Knoeri, C., Revell, R., Busch, J., and Steinberger, J.K.	2014	Assessing the dynamic material criticality of infrastructure transitions: A case of low carbon electricity	Applied Energy
85	Rosenau-Tornow, D., Buchholz, P., Riemann, A., and Wagner, M.	2009	Assessing the long-term supply risks for mineral raw materials—a combined evaluation of past and future trends	Resources Policy
86	Schillebeeckx, S.J.D, and George, G.	2013	The Scarcity of Natural Resources and its Organizational Implications: A Review and Conceptual Framework	Briefing or working paper
87	Schneider, L., Berger, M., Schüler-Hainsch, E., Knöfel, S., Ruhland, K., Mosig, J., Bach, V., and Finkbeiner, M.	2014	The economic resource scarcity potential (ESP) for evaluating resource use based on life cycle assessment	International Journal of Life Cycle Assessment
88	Speirs, J., Houari, Y., and Gross, R.	2013	Materials Availability: Comparison of material criticality studies—methodologies and results	Briefing or working paper
89	Speirs, J., McGlade, C., and Slade, R.	2015	Uncertainty in the availability of natural resources: Fossil fuels, critical metals and biomass	Energy Policy
90	Stavins, R.N.	2011	The Problem of the Commons: Still Unsettled after 100 Years	American Economic Review
91	Stern, P.C.	2011	Design principles for global commons: natural resources and emerging technologies	International Journal of the Commons
92	Tacconi, L., and Bennett, J.	1995	Economic implications of intergenerational equity for biodiversity conservation	Ecological Economics
93	UN	2004	United Nations Framework Classification for Fossil Energy and Mineral Resources	Report
94	US bureau of mines	1980	Principles of a Resource/Reserve Classification for Minerals	Report
95	US department of Energy	2010	Critical Materials Strategy	Report
96	Senate and House of Representatives of the United States of America in Congress assembled	1984	National Critical Materials Act of 1984	Public Law

Table A1. *Cont.*

nr.	Authors	Year	Title	Journal
97	Senate and House of Representatives of the United States of America in Congress assembled	1980	National Materials and Minerals Policy, Research and Development Act of 1980	Public Law
98	Whalen, K., and Peck, D.	2014	In the Loop—Sustainable, Circular Product Design and Critical Materials	International Journal of Automation Technology
99	Winterstetter, A., Laner, D., Rechberger, H., and Fellner, J.	2016	Integrating anthropogenic material stocks and flows into a modern resource classification framework: Challenges and potentials	Journal of Cleaner Production
100	Winterstetter, A., Laner, D., Rechberger, H., and Fellner, J.	2015	Framework for the evaluation of anthropogenic resources: A landfill mining case study Ð Resource or reserve?	Resources, Conservation and Recycling
101	World Trade Organization	2010	World Trade Report 2010: Trade in natural resources	Report
102	Xu, Z., Bradley, D.P., and Jakes, P.J.	1995	Measuring Forest Ecosystem Sustainability: A Resource Accounting Approach	Environmental Management
103	Zimmerman, E.W.	1951	World Resources and Industries: A Functional Appraisal of the Availability of Agricultural and Industrial Materials	book: Harper & Brothers, Publishers, New York
104	Zimmermann, T., and Gößling-Reisemann, S.	2013	Critical materials and dissipative losses: A screening study	Science of the Total Environment
105	Zwahlen, R.	1995	The sustainability of resources versus the sustainability of use: a comment	International Journal of Sustainable Development & World Ecology

Appendix E

Table A2. Clusters of journals in Figure 2.

nr.	Cluster Name	Included Journals (Number of Articles)
1	Ecological Economics	Ecological Economics (13)
2	Industrial production journals	Journal of Cleaner Production (5); Journal of Industrial Ecology (3); Waste and Resource Management (2); Materials and Design (1)
3	Resource journals	Resource Policy (8); Resources (2); Resources, Conservation and Recycling (1)
4	Interdisciplinary sustainability journals	International Journal of Life Cycle Assessment (4); Science of the Total Environment (2); Sustainability (1)
5	Technology journals	Environmental Science and Technology (2); Clean Technologies and Environmental Policy (1); International Journal of Automation Technology (1); New Biotechnology (1)
6	Geology and earth sciences journals	Applied Earth Science (1); Special Publications of the Geological Society, London (1); Ore Geology Review (1)
7	Business and management journals	Academy of Management Journal (1); Journal of Business Logistics (1)
8	Energy journals	Applied Energy (1); Energy Policy (1)
9	Others	Bulletin of University of Agricultural Sciences and Veterinary Medicine Cluj-Napoca. Agriculture (1); Journal of Physics D: Applied Physics (1)

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