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Green, circular, bio economy: A comparative analysis of sustainability avenues

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ABSTRACT

Despite their evidently different assumptions and operationalization strategies, the concepts of Circular Economy, Green Economy and Bioeconomy are joined by the common ideal to reconcile economic, environmental and social goals. The three concepts are currently mainstreamed in academia and policy making as key sustainability avenues, but a comparative analysis of such concepts is missing. The aim of this article is thus to comprehensively analyse the diversity within and between such concepts. The results are drawn from a bibliometric review of almost two thousand scientific articles published within the last three decades, coupled with a conceptual analysis. We find that, for what concerns environmental sustainability, Green Economy acts as an 'umbrella' concept, including elements from Circular Economy and Bioeconomy concepts (e.g. eco-efficiency; renewables), as well as additional ideas, e.g. nature-based solutions. In particular, Circular Economy and Bioeconomy are resource-focused, whereas in principle Green Economy acknowledges the underpinning role of all ecological processes. Regarding the social dimension, Green Economy is more inclusive of some aspects at local level (e.g. eco-tourism, education), while there is an emerging discussion in Bioeconomy literature around local processes in terms of biosecurity and rural policies. When considering weak/strong sustainability visions, all concepts remain limited in questioning economic growth. By comparing the different sustainability strategies promoted by these concepts we do not advocate for their substitutability, but for their clarification and reciprocal integration. The findings are discussed in light of the concepts' synergies and limits, with the purpose to inform research and policy implementation.

1. Introduction

As one of the most pressing challenge of our century, sustainability has been a main keyword in the global research and political agenda for decades (Garud and Gehman, 2012; Markard et al., 2012). So far, however, the simultaneous maximisation of ecological, economic and social goals [1] (UN, 1987) has proven to be extremely challenging. This is partly due to the disparate interpretations and applications of sustainability (Munda, 1997; Neumayer, 2003). Various sustainability concepts are proposed in research, policy making and private governance .[2] In this article, we review those that are currently being mainstreamed most vigorously at the global level as development and sustainability avenues: Circular economy, Green economy and Bioeconomy (CE, GE and BE) (USA, 2012; EAA, 2013; EC, 2015; Murray et al., 2015; OECD, 2011; UNEP, 2011). The choice of these three concepts is motivated by the fact that they all propose to adapt to or transform the current

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[1] Ecological goals include e.g. genetic diversity, resilience, biological productivity; economic goals include e.g. satisfaction of basic needs, enhancement of equity, increasing useful goods and services; and social goals include e.g. cultural diversity, institutional sustainability, social justice, participation (Barbier, 1987).

[2] Sustainability transitions, intended as 'fundamental transformation processes through which established socio-technical systems shift to more sustainable modes of production and consumption' (Markard et al., 2012).

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economy towards a more sustainable one. Loiseau et al. (2016) has identified CE, GE and BE as key and interconnected concepts in sustainability research, and has suggested a hierarchical relation among them. A relation among the concepts was also mentioned by Ollikainen (2014), Hagemann et al. (2016) and Székács (2017).

The concept of CE draws from the ideas of industrial ecology and industrial metabolism formulated during the 1970's and 1980's through a rethinking of the industrial processes (Frosch and Gallopoulos, 1989). Popularised during the 90's, the framing of CE contemplates that, in opposition to linear economy, economic actors would exert no net effects on the environment. This goal is mainly pursued by redesigning the life cycle of the 'product', with the aim to have minimal input and minimal production of system 'waste'. This involves a system for achieving net reductions at the organizational supply chain and industrial levels (Murray et al., 2015; The Ellen MacArthur Foundation, 2012). Since the underlying idea is the transformation of a certain industry by-product into a resource for a second industry, there is a strong emphasis on inter-sectorial dynamics and cooperation.

Even though a similar concept was already coined during the late 1980's (Pearce et al., 1989), GE has been mainstreamed after the 2012 UN Conference on Sustainable Development in Rio de Janeiro (Rio+20). GE aims at bringing together environmental conservation and poverty alleviation (Barbier, 2012). UNEP definition states that GE 'results in improved human well-being and social equity, while significantly reducing environmental risks and ecological scarcities. In its simplest expression, a GE can be thought of as one which is low carbon, resource efficient and socially inclusive' (UNEP, 2011, p. 1). According to the GE premise, different natural assets delivered by ecosystems (i.e. natural capital[3]) provide fundamental benefits for the economy and society, which are often invisible or disregarded.

A proto-conceptualization of BE is controversially attributed to Georgescu-Roegen (1975) and is work on bioeconomics, which advocated for a biophysical perspective to the economy. The current understanding of BE, developed over the last decade, is rooted in the idea that industrial inputs (e.g. material, chemicals, energy) should be derived from renewable biological resources, with research and innovation enabling the transformational process (Bugge et al., 2016; Kleinschmit et al., 2014; Pfau et al., 2014). In this context forestry and the agriculture and forest industry can play a fundamental role in providing bio-based substitutes for non-renewables (Ollikainen, 2014; Roos and Stendahl, 2015).

Despite CE, GE and BE being global concepts, regional trends exist. Individual concepts have been supported by dedicated national policies, and within that context taken up to be championed by dedicated sectors, such as forestry. For instance, China has introduced important policy instruments for CE since the early 2000's (Murray et al., 2015). The EU has formulated BE and CE (EC, 2012, 2015), and the USA have also dedicated attention to BE with a national blueprint (USA, 2012). GE has been promoted internationally by UNEP (2011), but has also trickled down into regional policies, for example in EU and USA (e.g. EAA, 2013).

As they gain momentum, individual concepts become influential to various societal actors (e.g. researchers, practitioners, NGO's, businesses) to support or legitimise their interests and activities. Each actor understands and applies these concepts in different ways, conferring on them a certain degree of internal diversity. For instance, Hodge et al. (2017) have recently suggested that in the context of the forest sector, BE can be considered a boundary object, "serving specific interests of different […] stakeholders". Previous literature has dedicated attention to the analysis of the diverse aspects and voices within the individual sustainability concepts (e.g. Boons et al., 2011; Borel-Saladin and Turok, 2013; Bugge et al., 2016; D'Amato et al., 2016).

Consequently, the three concepts show a wide variation in underlying assumptions, overall aims and objective, specific focus, level of detail in policy guidance and operationalization of sustainability. When compared, it appears they have different standpoints and possibly imply different sustainability visions.[4] However, a comprehensive comparative analysis of the three sustainability concepts is missing.[5] The aim of this article is thus to compare these three sustainability concepts: CE, GE, BE. The research questions addressed by this article are articulated as follows: *1. What are the publication patterns in time and space, the most popular publication platforms, and the keywords and topics that characterize the three concepts (CE, GE, BE), based on the available scientific literature? 2. Which sustainability narratives the three concepts (CE, GE, BE) align with, and which sustainability dimensions are emphasized, based on the keywords and topics emerging from the analysed literature?*

The results are discussed in light of the overlaps, divergences, synergies and limits of the three concepts, with links to possible policy implications of the findings. Illustrative examples are mostly drawn from the forest sector, which as a resource-based and mainly material economy is pivotal for climate regulation, water resources management, biodiversity and cultural values preservation, global and local development. Forest resources and associated industries are in fact strategic to the unfolding and implementation of CE, GE and BE concepts (Ollikainen, 2014; Roos and Stendahl, 2015). An additional value-added component of this article lays in that it constitutes, to our knowledge, one of the first examples of the applications of computational social science methods to sustainability research.

2. Methods

2.1. Bibliometric analysis

The bibliometric analysis was performed as follows. First, we searched literature related to CE, GE and BE using the search engine Web of Sciences (core collection). We included in our search the literature available from 1990 to present, by topic, using the following strings: "circular economy"; "green economy"; "bioeconomy" or "bio-economy". We obtained our datasets, i.e. three bodies of literature, one for each concept (Table 1). For the three datasets, we downloaded the full record and cited references (including 67 variables).

The three sets of records (CE, GE and BE bodies of literature) were considered as individual corpi, where a corpus is defined in text mining as a collection of text, generally in the form of several documents. The analysis was performed with the software **R** 3.3.2 (R Development Core Team, 2016), using an adaptation of the source code provided by the Network Analysis Interface for Literature Studies (NAILS) project (Knutas et al., 2015).[6] The analysis

[3] Nature is understood to be essential to the health and growth of economies, societies and individuals through the provision of ecosystem services. Building on this, nature can be understood as delivering natural assets and hence be seen as "natural capital", existing alongside manufactured, financial, social and human capital (ten Brink et al., 2012).

[4] According to weak sustainability, natural, social and economic capital are substitutable. According to strong sustainability, substitutability is technically impossible or inefficient and/or normatively undesirable (Neumayer, 2003).

[5] A recent review by Loiseau et al. (2016) has reviewed the concepts of GE, and how it relates to CE and BE. Loiseau et al. (2016) adopts the assumption that GE is an overarching framework for CE and BE, and it thus only reviews the literature on GE, excluding the literature from CE and BE. Our analysis, instead, does not start from the assumption that CE and BE are hierarchically subordinated to GE.

[6] The adaptation of the code used in this study is available at: https://github.com/NilsDroste/CE-GE-BE-LDA-topic-models.

Table 1
A summary of the bibliometric analysis, including search engines, strings, dataset size and type of analysis.

Search engine	Strings searched	Dataset size	Analysis
Web of Science	"circular economy" "green economy" "bioeconomy" or "bio-economy"	864 615 464	Temporal and geographical distribution of publications; most popular publication platforms; salient keywords and emerging topics.

provides descriptive statistics such as number of publications per year; geographical distribution of publications by country (based on authors' affiliations); most popular publication platforms, such as journals, books and conference proceedings. This information is directly derived from the Web of Science records. Furthermore, for each corpus (i.e. CE, GE and BE bodies of literature) the analysis includes a list of salient keyword terms associated with the overall corpus; and six topics, with a list of associated topic-specific keywords. Such analysis is based on latent Dirichlet allocation (LDA) (Blei et al., 2003; cf. Pritchard et al., 2000) and it is supported by the *LDAvis* 0.3.3 package in **R** (Sievert and Shirley, 2014).

The underpinning assumption behind LDA is a probabilistic Bayesian network-based model according to which each document is characterized by certain topics, and each topic can be defined by a specific set of words, which co-occur with a certain probability. In other words, topics within documents are defined by a cohort of words that appear often together. Thereby, we can derive the topics that are representative of each concept (CE, GE and BE), describing their content in general, and their internal topics in particular.

For each concept, we programmed the model to highlight six topics. As mentioned, each topic is characterized by a set of keywords. Keywords can be generic to the entire corpus, or specific to one or few topics. The model provides the option to identify the keywords that are specific to certain topics. The specificity of the keyword is calculated as the ratio of the frequency of the keyword in a certain topic to the overall keyword frequency in the overall corpus (Chuang et al., 2012), given a weight parameter λ ($0 \leq \lambda \leq 1$). Decreasing the value of the weight parameter λ reveals topic-specific keywords; increasing λ reveals keywords that are common to the entire corpus (Sievert and Shirley, 2014). Based on the given keywords, we interpreted the meaning of each topic.[7]

The model also calculates the distance between topics on a scatterplot, which approximates the semantic relationship between topics based on multidimensional scaling (MDS). Similarly, to factor analysis, MDS allows the level of similarity or distance between investigated objects to be visualized. Inter-topic distance is calculated using Jensen-Shannon divergence (Sievert and Shirley, 2014). The results of the LDA analysis can be further explored through a website which we invite the reader to access at: http://www.ufz.de/index.php?en=42249.

2.2. Conceptualization of CE, GE and BE within sustainability

Based on the salient keywords and topics revealed by the bibliometric analysis (section 2.1), we performed a conceptual analysis to identify the sustainability narratives and aspects predominant in each concept (CE, GE and BE). Typically, the meaning of sustainability has been declined differently according to the actors involved and the context (Garud and Gehman, 2012).

We refer to the sustainability narratives identified by Franceschini and Pansera (2015), which describe, in particular, the economic dimension of sustainability, represented by growth or degrowth. Such narratives include: business-as-usual, relative decoupling, green growth, limits to growth, absolute decoupling, green frugality (Table 2). When embedding these narratives into a discourse analysis proposed by Arts et al. (2010, p. 60), the business-as-usual narrative relates to the modernity discourse, based on "economic growth, industrialisation, control over natural and social resources" to which the limits to growth narrative is a critical response; relative and absolute decoupling belong to the ecological modernisation discourse, which argues for a reconciliation of economic growth and environmental protection through technological progress; sustainable development, popularised by the Brundtland report, is an overarching discourse for green growth and frugality.

In our conceptualization, we also identified the sustainability aspects of the social and environmental dimensions most emphasized in CE, GE and BE concepts. To gather a comprehensive account of the aspects that characterise environmental and social sustainability, we refer to existing literature (Dempsey et al., 2011; Moldan et al., 2012) (Table 3). We use Tables 2 and 3 as a baseline for comparison, and based on the keywords and topics emerging from the bibliometric analysis, we identified the alignment of CE, GE and BE with the sustainability narratives and with various aspects of the social and environmental dimensions.

2.3. Validity, reliability and limitations

The data collection for the review is limited in that we only searched for direct terms "circular economy"; "green economy"; "bioeconomy". These however have various synonyms and associated concepts, such as industrial ecology/metabolism; green growth; bio-based/knowledge-based economy. We decided however not to use ancillary search terms, to guarantee a balanced search strategy and comparability of the datasets. Regarding the search strategy, we can exclude that the three datasets overlap, i.e. that the same articles are found when searching for CE, GE and BE literature individually. In fact, in Web of Science, only 7 articles were found that contain both the search strings "circular economy" and "bioeconomy" (or "bio-economy"); only 6 articles contain both the search strings "circular economy" and "green economy"; and only 5 articles contain both the search strings "green economy" and "bioeconomy" (or "bio-economy").

To verify that our sample retrieved from Web of Science was representative of the existing literature, we also searched Scopus (titles, abstract and keywords) from 1990 to present, using the following strings: {circular economy}; {green economy}; {bio-economy} or {bioeconomy}. From Scopus we retrieved 1061, 931 and 646 articles respectively, showing similar relative sizes for CE, GE and BE literature. In addition, using Scopus feature "analyse search results", we obtained a timeline of the publications per year, which we compared to the one we performed using the Web of Science dataset. This allowed us to verify that the temporal distributions of CE, GE and BE were similar in Scopus and Web of Science. Both timelines do not show wide variations in the distribution of CE, GE and BE literature, signalling that a comparison of the three literature bodies is feasible (cf. Franceschini et al., 2016 about methods).

Regarding the geographical distribution of the literature, it is important to note that the analysis shows the countries where the

[7] Based on the recommendation by Sievert and Shirley (2014), in our study the interpretation was performed with $\lambda = 0.6$, but supported by observing the results given different values of lambda as well. All the plots provided in this article report results with $\lambda = 0.6$. By accessing the website link provided in section 2.1, the reader can verify the results at different value of λ.

Table 2
Six narratives describing the economic dimension of sustainability (based on Franceschini and Pansera, 2015).

Narrative	Definition
Business-as-usual	Economic growth is prioritized, environmental sustainability is not explicitly pursued. Sustainability is given by the efficient conversion of natural capital into human-made capital.
Relative decoupling	Natural and human-made capitals cannot be considered interchangeable. Negative environmental impacts can be partly avoided through increasing eco-efficiency in pursuing economic growth.
Green growth	Economic growth and environmental sustainability can be reconciled and can have mutual positive feedback. This process if fuelled by nature-based solutions, i.e. ecological adaptation and resilience; these are conceived in opposition of or in addition to techno-knowledge solutions.
Limits to growth	Technological development does not meet the needs of human society. The natural limits of the planet produce a shrink or collapse in economic growth.
Absolute decoupling	Natural and human-made capitals cannot be considered interchangeable. Economic growth is not excluded as long as negative environmental impacts can be completely avoided through increasing eco-efficiency. Environmental sustainability is thus prioritized over growth.
Green frugality	Awareness of ecological limits and limits to growth are sought; techno-knowledge solutions are substituted or complemented with nature-based solutions, ecological adaptation and resilience.[a]

[a] Concrete solutions to the management of natural resources that build on the understanding of ecosystem services, e.g. using restoration of wetlands' ability to retain and purify water as part of water management (Kettunen and Ten Brink, 2015).

Table 3
Main aspects included in the social and environmental dimensions of sustainability.

Sustainability dimensions	Definition
Social	Education and training, social justice (e.g. inter- and intra-generational), participation and democracy, health, quality of life and well-being, social inclusion, social capital, community network, safety, mixed tenure, employment and income (safety and equality), social order and cohesion, cultural traditions, recreation and tourism.
Environmental	Water, carbon and nutrient cycles (including emissions and waste); greening cities and logistics; quality of energy source and efficiency in production and use; maintenance of biodiversity, ecosystems and related services.

literature is produced (based on authors' affiliations) but it does not provide information on the geographical coverage of the studies. Literature published in languages other than English was not considered, and thus the analysis might not represent a global sample. Furthermore, the analysis was only performed on scientific publications, thus excluding other publication types such as policy documents, project reports and other grey literature.

To ensure a successful analysis of the data, the text material was pre-processed through tokenization and stemming[8] (Grün and Hornik, 2011). Tokenization separates tokens, i.e. meaningful elements of the text (e.g. words) from spaces, punctuation, acronyms, numbers, hyphens or other symbols. Terms with a length below a certain minimum are removed. Stemming reduces a word to its root grammatical form. In addition, terms which occur fewer than 5 times have been removed from the analysis.

LDA is still a developing technique, but it allows for the content analysis of large amount of text wording, which would be extremely time consuming if processed manually. While humans can easily interpret the meaning of text and words, a software is limited in that it may not be able to perceive, for instance, the level of abstraction, the multiple/contextual meanings or sentiment of a word. That information is thus lost in the results, making the interpretation of some keywords difficult. For example, the keyword 'employment' may be found frequently in a corpus or topic, but it is not possible to know in which context the word has been used. As a result, it is not possible to attribute any qualitative or value connotation to a given term.

Another limitation is that the number of topics within each individual corpus does not emerge from the analysis, but needs to be set a priori. Our aim was to highlight enough topics within each concept to uncover the internal variability, without having an excessive number of topics that would create noise and hamper comparability among concepts. Choosing an appropriate number of topics to be highlighted thus represents a trade-off between information loss and information overload. The number of topics needed to represent most comprehensively the diversity of the dataset can be calculated with a tuning algorithm. According to the algorithm, the optimal number of topics for our dataset was over 200, which we did not consider easily interpretable[9]. We thus decided to set the model to identify six topics, which is the default option suggested by Knutas et al. (2015) source code implementation of *LDAvis* (Sievert and Shirley, 2014). This decision was reinforced by the analysis, since the six topics appear to have a critical meaning and *raison d'etre* in all concepts.

3. Results

3.1. Inter and intra-diversity of CE, GE and BE

In total, the CE literature body is the largest with 864 publications, GE follows with 615 and BE is the smallest corpus with 464 entries. CE and BE concepts have seen an increase in publication material since the early 2000's, while GE has become popular after 2010 (Fig. 1). The geographical distribution varies among the different bodies of literature (Fig. 2). CE is extremely prosperous in Chinese literature, while in the USA GE and BE literature are predominant over CE. In Europe, CE, GE and BE are all consistently researched. Other notable sources of literature for CE, GE and BE include: Australia, Brazil, Canada, Russia, and South Africa. GE is the discourse that is most widespread at the global level, including publication from various developing countries. Conversely, CE and BE are more researched in transitioning and developed economies' institutes.

The most popular publication platforms (Fig. 3) for CE are journals dedicated to industrial ecology, cleaner production and material flow analysis. GE research is more often published in environmental or ecological economics and natural resources journals. BE research occurs in a mixed set of journals, often dedicated to biotechnology sector-oriented fields, such as forestry and agriculture.

Figs. 4–6 are a snapshot of the results from the LDA analysis (the results are interactive and can be best explored at: http://www.ufz.de/index.php?en=42249). The figures show: a. The most salient keyword terms found in the articles dealing respectively with CE, GE and BE (right part of the figure); and b. The semantic distance between the six topics (1–6), based on co-occurrence of words (left

[8] An update to the **R** package was released after the manuscript revision. The new package includes a more refined the stemming procedure.

[9] We employed the *ldatuning* package provided by (Murzintcev, 2015).

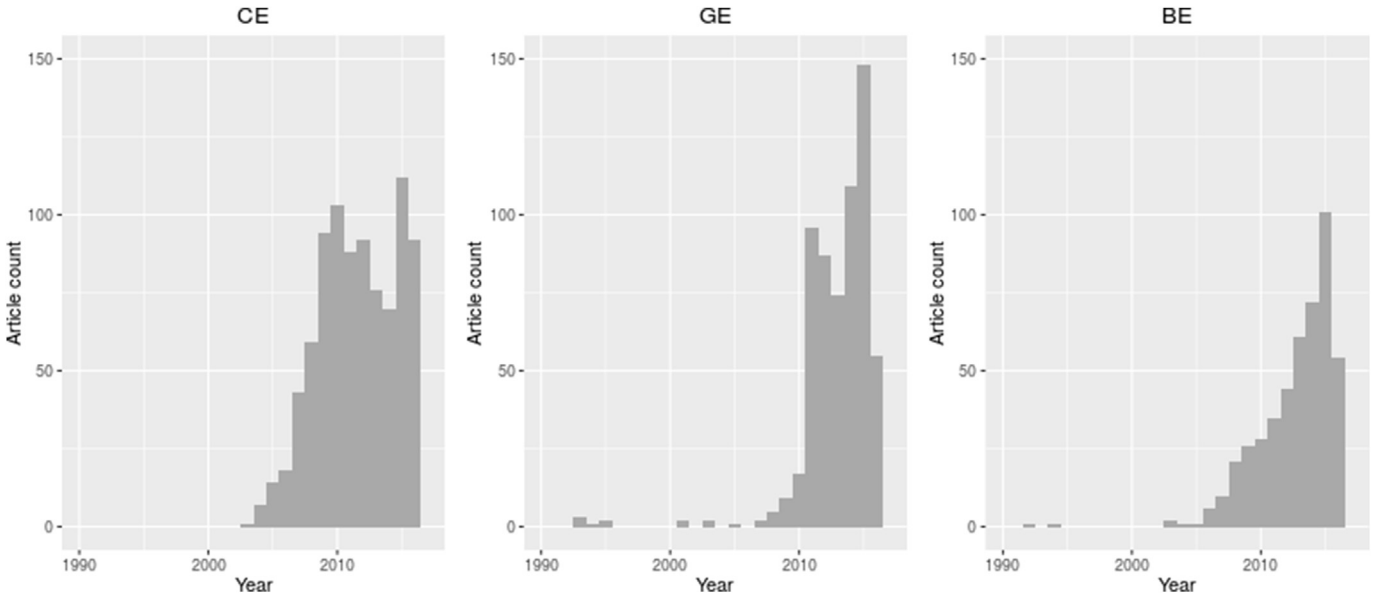

Fig. 1. Publication trends for CE, GE and BE literature from 1990 to present.

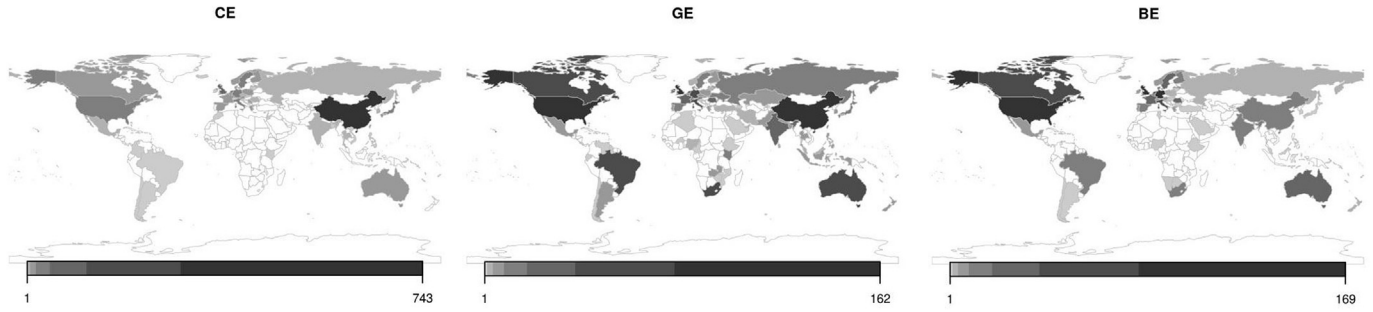

Fig. 2. Geographical provenience of the literature. The colour scale refers to the number of articles.

part of the figure). Note that the topics are visualized as circle areas; the circle size represents the proportion of each topic within the corpus; the number in the circle represents the topic number (see Table 4 for a comparative view of the six topics in CE, GE and BE). A more in-depth analysis of the individual topics within each concept is provided in Table 4 and in Figs. 8–10 in the appendix.

Salient keywords associated with the CE literature include, for instance, economy, development, circular, industrial, system, environmental, waste, energy, resource and recycling (Fig. 4). The analysis of topics reveals that topic 1, associated with keywords such as industry, resources, city, urban, construction and mining, identifies the research area of sustainable development in industrialization and urbanization. Topic 4 appears to be more methodological oriented, concerning techniques for evaluating productive efficiency, especially in the context of logistic/supply chain management systems. Topics 3 and 6 clearly identify respectively industrial symbiosis in the context of the European Community, and supply chain greening. Topic 2 is associated with keywords that hint at life cycle assessment, such as waste, recycling, life, recovery, flow and re-use. Topic 5 represents the research area dedicated to carbon emission and energy, especially in the context of production plants. In the inter-topic distance map, topics there are two clear clusters of topics: 1 and 4 in quadrant I, and 3 and 6 in quadrant IV.

For what concerns GE, there is a cluster of overlapping topics in quadrant III. Topic 1 is identified with sustainable development, and associated with keywords such as Rio [UN summit], discourse, justice and transitions; topic 2 is identified with green investments, especially in urban context, and associated with keywords such as capital, investment, urban and cities. Topic 3 relates to the social dimension of tourism, business, education, employment. Topic 5 is the closest to the cluster of topics 1, 2 and 3, and it is characterized by keywords related to CE, such as recycling, re-use, reduction product and life cycle. Topic 4 in quadrant I is related to BE, with keywords such as biomass and renewables in energy production. Topic 6 clearly identified the conservation and land use aspect of GE, including keywords such as water, land, biodiversity, food, security.

The topics found in the BE literature include two clusters of overlapping topics including respectively topics 1 and 4, and 2 and 5. Topic 3 is positioned near the second cluster, while topic 6 is in a more isolated position. Topic 1 and 4 identify respectively with the research areas dedicated to biomass and renewables in energy production and biotechnology applications in materials science. These can be interpreted as low-high value-added bio-based products. Topic 2 relates to the rural policies especially in Europe, and it is also associated with the ideas of innovation and knowledge-based bioeconomy. Topic 5 relates to biomass supply/demand -related research (especially wood), with several keyword terms related to scientific methodological aspects (study, data, models). Topic 3 include keywords such as science, blood, stem and genomics, which can be clearly identified with biotechnology research and applications in health science. Topic 6 is about biosecurity, i.e. systems and practices aiming at reducing risks in agri/environmental communities (e.g. management of pests, diseases, invasive species). The topic is defined by words such as crops, species, risk, yield and invasive.

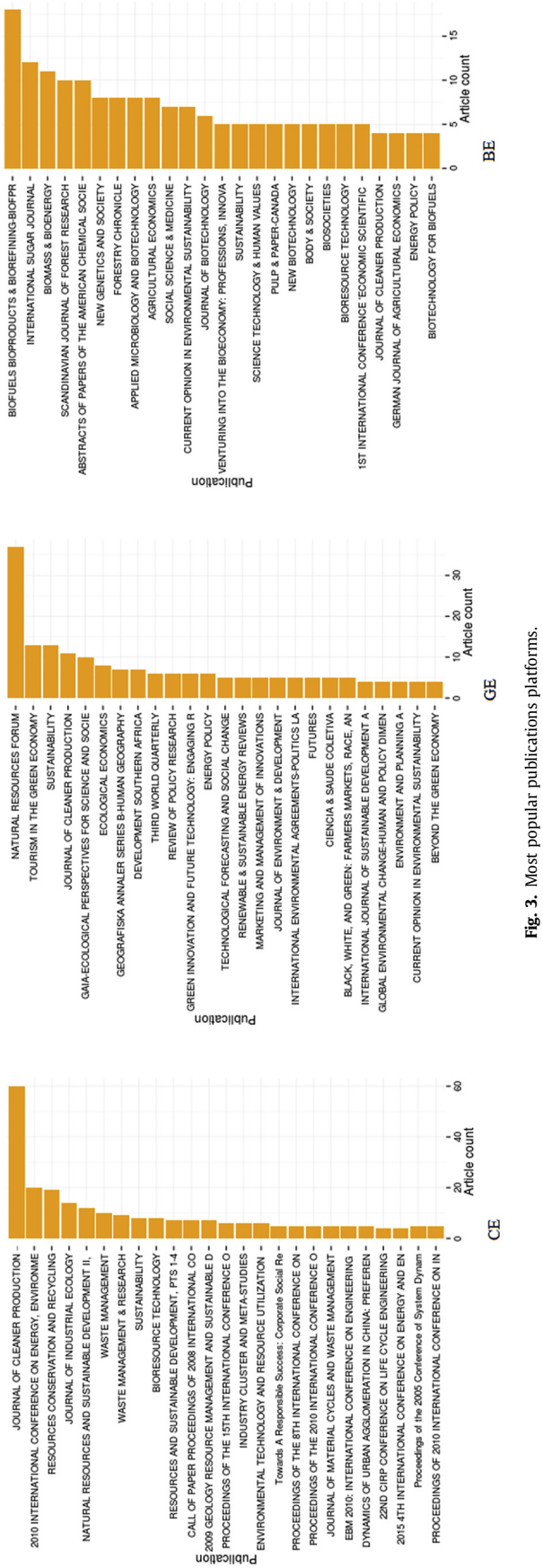

Fig. 3. Most popular publications platforms.

3.2. CE, GE and BE within sustainability

In Fig. 7 we position the three concepts within/across different sustainability narratives based on a conceptual framework adapted from Franceschini and Pansera (2015), see also section 2.2. It should be noted that the position of the concepts does not represent a value judgment. The concepts position is merely defined by the means they use to achieve sustainability. The x-axis represents the change to pursue sustainability, including a non-eco[logical] scenario, a techno-knowledge fix (e.g. eco-efficiency and eco-innovation), and nature-based solutions, including territorial adaptation and resilience. The y-axis refers to growth. Weak/strong sustainability is cross-cutting in the diagram. Based on these coordinates six narratives are identified: business-as-usual, relative decoupling, green growth, limits to growth, absolute decoupling and green frugality (descriptions in Table 2).

Based on the keywords and topics obtained through the bibliometric analysis, we determined the position of CE, GE and BE within the conceptual framework. All three concepts (CE, GE and BE) imply economic growth -based development, they are thus positioned towards increasing growth on y-axis. For what concern the x-axis, each concept seems to propose different means to pursue sustainability. CE topics typically revolve around decoupling driven by technological innovation, specifically recycling and eco-efficiency. The observed internal diversity of BE literature causes this concept to be split across three narratives - although it is centred in the relative decoupling narrative. Since BE literature does not explicitly refer to circularity, eco-efficiency and resource saving, a simple substitution of non-renewables with renewables does not guarantee sustainability. In fact, bio-based resources are functionally finite and a huge increase in BE development could quickly reach the limits of sustainability. Under such a scenario, BE could thus be considered business as usual. However, BE literature also includes topics 3 and 6, which are about making use of residual biomass streams with the help of new technologies (e.g. biochemical and compounds). In other words, residual volumes of biomass are salvaged to produce something new, and this relates to efficiency and resource savings, which can increase resource efficiency. Consideration about the other potential uses of such residual streams is important in determining whether this approach is sustainable in the long term. For example, a certain proportion of forest biomass and agricultural residues may better serve sustainability goals by being left *in situ* and contributing to ecosystem function. This is partially addressed by the inclusion of a research area around biosecurity (topic 6) in the BE literature, which is about environmental risk management, especially in agricultural and other intensively managed systems. In this sense, biosecurity has (not fully expressed) potential to include nature-based solutions and a landscape approach, extending thus to territorial adaptation and resilience.

Finally, GE includes elements from both BE and CE (topics 4 and 5), but remaining topics (1, 2, 3 and 6) are more explicitly oriented towards nature-based solutions green investments, green employment and conservation. GE can therefore be positioned in between the relative decoupling and the green growth narrative, with a weight on the latter.

Based on the keywords and topic analysis, we identified the focus of each concepts regarding both the environmental and social sustainability dimensions (Table 5). Concerning environmental sustainability, several salient keywords were associated with environmental sustainability among the top 30 found in CE, including for instance waste, energy, recycling, green, resource, carbon and ecological. “Species” is the only keyword found in BE explicitly associated with environmental sustainability, and is mostly found under topic 6 ‘biosecurity'. Several keywords found in GE related to environmental sustainability, including energy, green, renewable, water, eco, carbon, climate, waste and natural. While all concepts involve environmental sustainability, CE keywords and

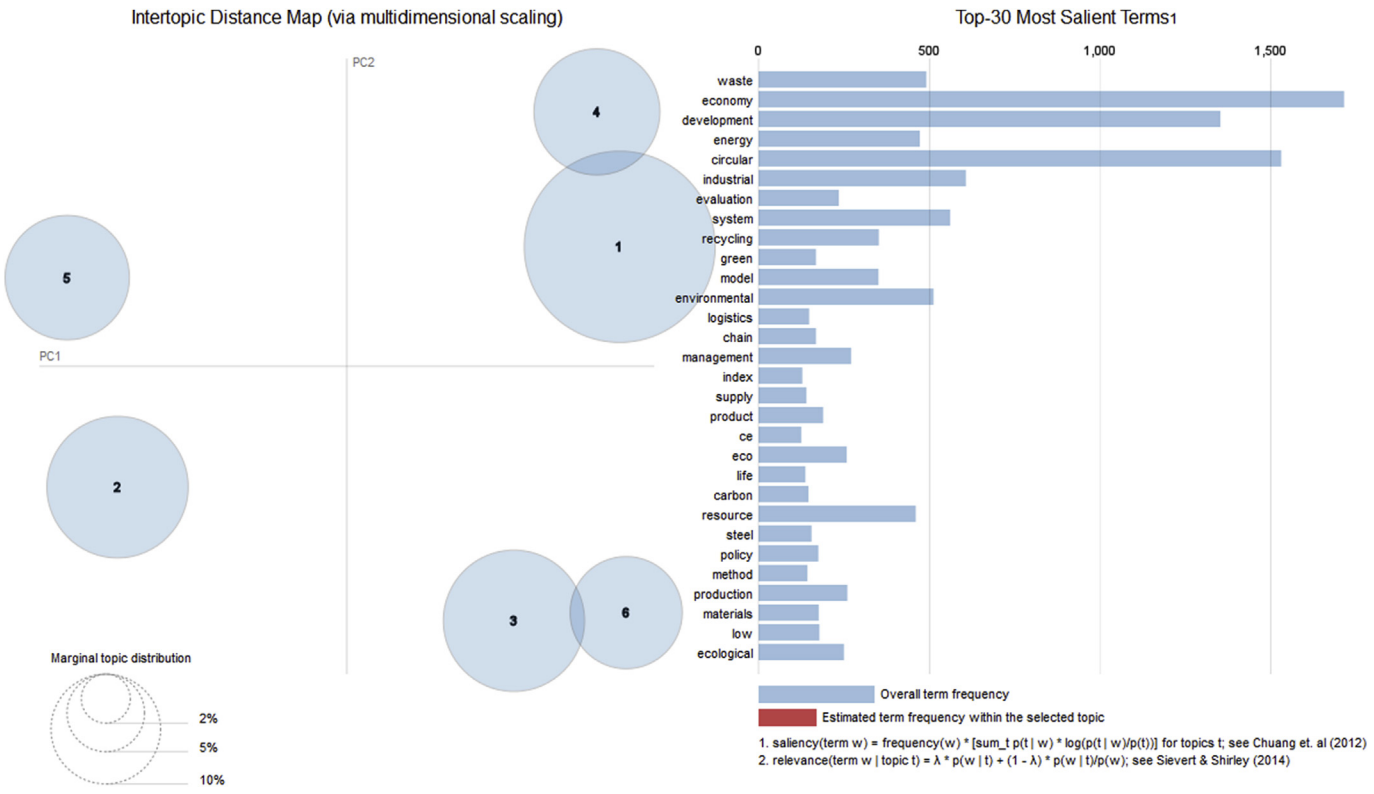

Fig. 4. Top 30 salient keywords in CE literature and inter-topic distance. Note: in the bottom-right part of the figure, the numbers 1. and 2. (saliency and relevance) do not refer to the numbers of the circles in the scatterplot on the left part of the figure; the estimated term frequency (represented in red) is not shown in this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

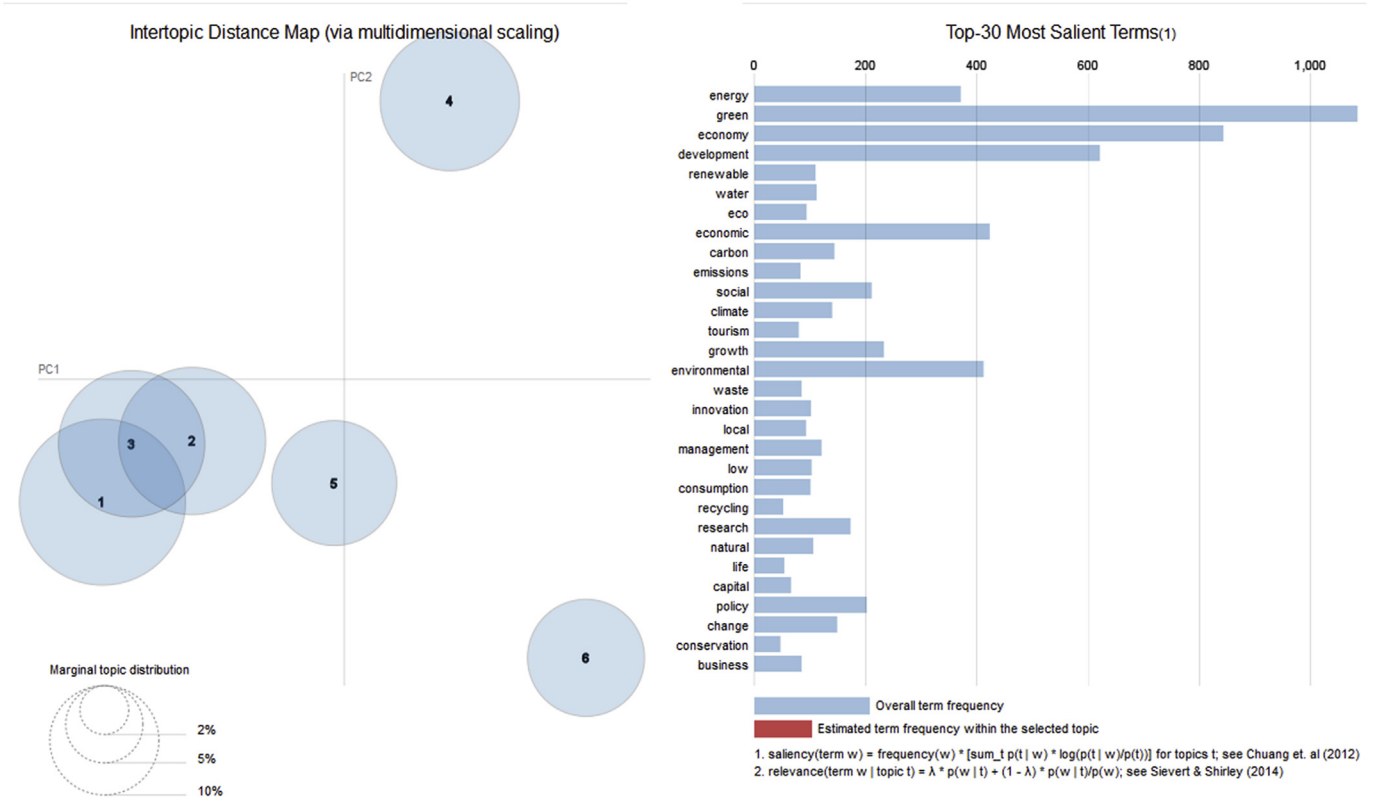

Fig. 5. Top 30 salient keywords in GE literature and inter-topic distance. Note: in the bottom-right part of the figure, the numbers 1. and 2. (saliency and relevance) do not refer to the numbers of the circles in the scatterplot on the left part of the figure; the estimated term frequency (represented in red) is not shown in this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

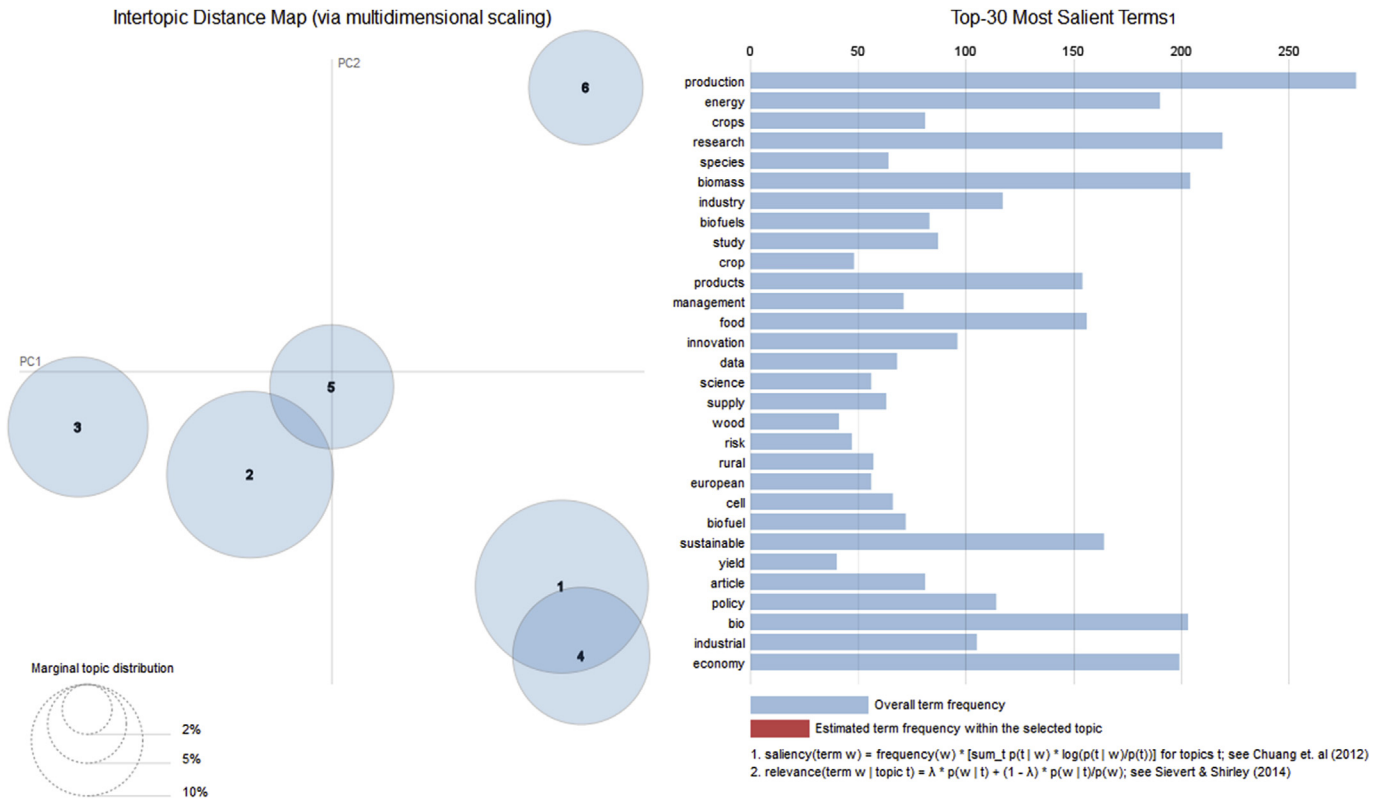

Fig. 6. Top 30 salient keywords in BE literature and inter-topic distance. Note: in the bottom-right part of the figure, the numbers 1. and 2. (saliency and relevance) do not refer to the numbers of the circles in the scatterplot on the left part of the figure; the estimated term frequency (represented in red) is not shown in this figure. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

topics hint to recycling/re-use, eco-efficiency, industrial greening and symbiosis. On the other hand, GE and BE referred more explicitly to ecological processes, for instance through conservation and biosecurity, respectively.

Regarding the social dimension, significant salient keywords among the top 30 found in GE are 'social' and 'business' mainly under topics 1, 2 and 3. These topics refer to the social dimension as they deal with sustainable development (especially Rio+20 and the related equity dimension), with green investments, tourism and business, as well as the education sphere. Salient words found in BE are 'research' and 'science'. These refer to the social dimension especially for what concerns research and applications in health sciences, but also in terms of BE policies for rural development. There is no explicit reference to the social dimension in CE salient keywords, even though topic 1 implies social considerations, such as economy, development and user perspectives.

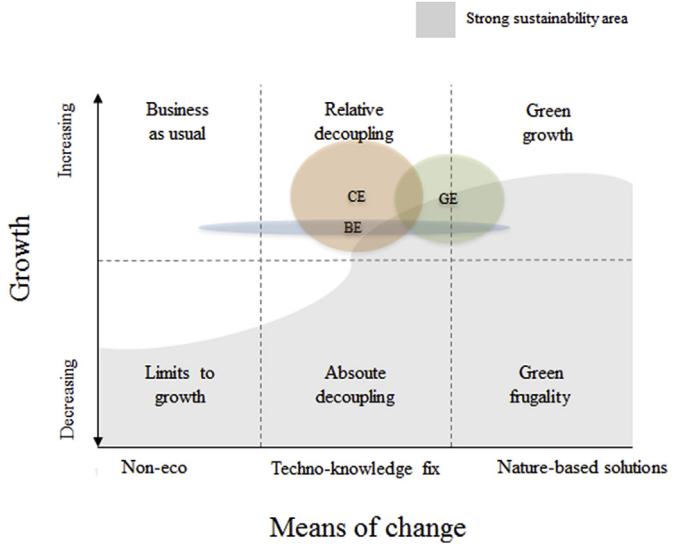

Fig. 7. The position of the sustainability concepts along different combinations of growth and means of change. Figure modified from Franceschini and Pansera (2015). The size of the circles represents the amount of retrieved literature dealing with the individual concept.

4. Discussion

Even though the origins underpinning CE, GE, BE date back to the 1970's and 1980's, the three concepts have all been concretely popularised after the 2000's. The geographical distribution of the three concepts shows that BE is particularly popular in the EU, which can be expected since the concept has been consistently promoted in EU policy making since the early 2000's (e.g. Lisbon Agenda) as a key aspect to competitiveness and economic growth, until the adoption of a BE strategy in 2012 (Bioeconomy, 2012). BE is also strong in the USA, which has recently released a national blueprint (USA, 2012). China has produced the most consistent amount of literature regarding CE, an expected finding given the political steering towards the concept exercised by the government in the recent years. Our results show that popularity of CE in research has increased consistently after 2008, when a national law was introduced in China to promote waste reduction and recycling in key industries (Murray et al., 2015). There has also been a notable growth of the literature in 2015, probably indirectly fuelled by national, European and global policy developments in this area, such as the 2015 UN Climate Change Conference (COP21) and the 2015 EU communication on a CE action plan (EC, 2015). CE research is strong in Europe, and expected to increase in the future through the implementation of the proposed strategy.

Table 4
Six main topics emerging in CE, GE and BE concepts.

Topic	CE	GE	BE
1	Sustainable development in industrialization and urbanization	Sustainable development	Biomass and renewables in energy production
2	Recycling in products life cycle for waste reduction	Green investments, especially in urban context	Rural policies esp. in Europe
3	Industrial symbiosis, especially in EU	Tourism, business, education, employment	Biotechnology applications in health science
4	Efficiency evaluation techniques in logistic/supply chain management systems	Biomass and renewables in energy production	Biotechnology applications in materials science
5	Carbon emission and energy in production plants	Recycling, re-use, reduction in products life cycle	Biomass supply/demand, especially wood
6	Greening the supply chain	Conservation and land use	Biosecurity

Table 5
Main aspects included in CE, GE and BE concepts in regard to the social and environmental dimensions of sustainability.

Concepts	Sustainability dimensions	
	Environmental	Social
CE	Recycling/re-use, efficiency, industrial symbiosis, greener supply chain.	Economy, development, utilization.
GE	Conservation, water, land, biodiversity, food, security.	Sustainable development; Green investments, tourism, business, employment, education.
BE	Biosecurity, crops, species, risk, yield, invasive.	Rural policies; Research and applications in health science.

GE is mostly researched in EU, but the research community in the USA and China has also produced a consistent number of articles on the topic. It is also worth noting that GE appears to be the most widespread research topic with various contributions from developing and transitioning economies – which underlines its global development policy implications. The international nature of GE is also linked to the fact that GE is proposed at global level by UNEP. In fact, the GE increased popularity shown by our results could be interpreted as a reaction to the publication of the GE report by UNEP (2011).

As mentioned in the limitations section 2.3, the geographical distribution shows the countries where the literature is produced (based on authors' affiliations), and it is therefore skewed towards developed countries which may appear more academically active on Web of Science. In addition, it should be noted that even though the same concept may be popular in multiple countries, intrinsic differences may exist in how such concepts are treated in different countries. For example, the European Commission (Bioeconomy, 2012) defines BE as 'the production of renewable biological resources and the conversion of these resources and waste streams into value added products, such as food, feed, bio-based products and bioenergy', including both traditional and emerging sectors, i.e. 'agriculture, forestry, fisheries, food and pulp and paper production, as well as parts of chemical, biotechnological and energy industries'. In the US, BE strategy focuses more narrowly on synthetic biology, excluding the cross-sector perspective (USA, 2012). Given that the literature from some countries or regions could be more represented in the data (especially in the case of CE), the content analysis could be skewed towards the conceptualization dominant in that country or area. Moreover, our analysis excludes literature that, without actually using these terms, deals with CE, GE or BE. This limitation fails to fully capture the historical development of such concepts, which have stemmed and evolved from parallel terms (e.g. industrial ecology/metabolism; green growth; bio-based/knowledge-based economy).

Regarding the publication platforms of the three concepts, CE is generally published in 'industrial ecology'- oriented journals; GE in environmental or ecological economics journals; and BE in technical and sector-oriented journals. In other words, the platforms where the articles are published exhibit a wide variety and reflect the intra- and inter-diversity of the concepts.

The analysis of salient keyword terms and topics reveals that CE literature is more homogeneous that GE and BE literature, both of which harbour a certain internal diversity regarding research lines and content. Literature on CE almost monolithically revolves around resource-efficiency, increasing resource productivity and decoupling resource utilization from economic growth. CE is embedded in the context of industrial systems and does not account sufficiently for social and local dynamics. This was also recorded by Murray et al. (2015), who call for the incorporation of ecological knowledge and social and human dimension into economic models and systems.

Generally, BE advocates that industrial inputs (material, chemicals, energy) should be derived from renewable biological resources, with research and innovation enabling the transformational process (McCormick and Kautto, 2013; Pfau et al., 2014). A central node of tension will be between an exclusively technology-based approach versus a more socio-ecological approach (Priefer et al., 2017). Part of BE literature focuses on traditional bio-based materials and energy. In this context, if no emphasis is attributed to circularity, BE is at risk of becoming a 'business as usual' scenario. A share of BE literature, however, also deals with the role of science-based knowledge and innovation, such as recovering residual biomass streams to create high added value products. In addition, a clear share of the literature is dedicated to biosecurity issues, which recall more ecologically-oriented aspects. The topic of biosecurity under BE presents several links with GE-related territorial adaptation and resilience through nature-based solutions and a landscape approach. Examples include shifting from exotic to local species/varieties on unproductive and economically marginal land (Sheppard et al., 2011); or bioremediation in agro-environmental systems (Gillespie and Philp, 2013). Biosecurity, however, is not always treated in a comprehensive manner, with the exclusion of broader aspects of sustainability like ecosystem health (Sheppard et al., 2011).

The social aspects considered in the current literature on BE mainly concern human health and nutrition, and rural development. In line with our findings, Bugge et al. (2016) has recently identified three ideal BE visions: a bio-technology vision, a bio-resource vision, and a bio-ecology vision. The first two are technology-oriented and attribute a central role to development of new commercial applications for example in the wood products and health sectors; environmental sustainability is possible, but secondary to economic growth and job creation. The third highlights the importance of ecological processes that 'optimise the use of energy and nutrients, promote biodiversity, and avoid […] soil

Table 6
Overlaps, limits, synergies and divergences of CE, GE and BE.

Overlaps	Divergences	Shared limits	Synergies
Energy, emissions and natural resources utilization; Eco-efficiency in CE and GE.	CE and BE resource-centred (with a different focus), while GE addresses all natural processes; CE focussed on urbanization and BE on rural development.	Fail to question the growth paradigm; Incomplete in addressing all aspects of sustainability dimensions.	Circular Bioeconomy; GE as an umbrella concept.

degradation' (Bugge et al., 2016 p. 13). Pülzl et al. (2014) and Kitchen and Marsden (2011) argue that generally BE is more related to global economic growth and technologic development, while local and social considerations are missing. We find, however, that space for local processes within the BE concept can be found in the issues of biosecurity and rural policies. Bioenergy is also an aspect with strong local implications (Johnson and Altman, 2014).

GE literature hosts ideas from both BE and GE, such as biomass and renewables and recycling, re-use and reduction in products life cycle. GE research, however, focused on additional sustainability aspects oriented towards the social dimension of green jobs, eco-tourism and education; as well as towards nature conservation. GE is thus particularly characterized by the idea of nature-based solution in local contexts and takes explicitly into account ecological and social dimension (e.g. by engaging with ecosystem services and trade-offs).

The distance between topics within each concept is also an interesting source of information. For instance, within the GE literature, topic 6 dedicated to conservation and land use is distant from the other topics. Similarly, topic 6 in BE literature, dedicated to biosecurity, is very distant from the other topics found in BE literature. Such distance signifies the linguistic diversity of the topics. We can therefore deduce that biosecurity is expressed and discussed with different terminology than other topics related to BE. Based on the comparative analysis of salient keyword terms and topics, we discuss BE, CE and GE in terms of overlap, divergences, limits and synergies (Table 6). Regarding overlaps and divergences, CE and BE are about mobilising resources and increasing resource productivity, through recycling and reducing in production process (CE) and through primary production and adapted end uses of renewables (BE). In other words, CE is dominantly about how resources are used, while BE is about what resources are used. Within BE, eco-efficiency is not excluded, but not explicitly ensured. CE is more focused on urban processes, while BE includes rural development.

GE includes both the ideas of resource-efficiency[10] and renewables (including biomass-based), but it mainly envisions a green growth through nature-based solutions and investments dedicated to promoting restoration, conservation and sustainable management of natural capital through social inclusivity. GE seems also more inclusive of some aspects of the social dimension at local level (e.g. eco-tourism and enterprises, education) and it is the only narrative to specifically address the sustainable development aspects of justice and public participation. GE also refers to various ecological processes, and thus embodies a greater variety of disciplinary perspectives. In fact, while CE and BE are resource focused (i.e. provisioning ecosystem services),[11] GE in principle acknowledges the underpinning role of biodiversity and all ecosystem services, including regulating and cultural services. In this sense, GE postulates that encouraging the conservation and restoration of natural processes (e.g. water purification, carbon storage) can be more cost-effective in the long run compared to eco-efficiency or the use of bio-based resources alone. For instance, while the role of biofuels is a key topic in BE, it is seen under a more critical light in GE, due to the imposition of trade-offs with other ecosystem services, e.g. in plantation forestry (Ollikainen, 2014).

In line with our findings, according to which GE includes some elements from CE and BE, Kleinschmit et al. (2014, p. 403) has suggested that BE 'can be understood as a part of green economy, but emphasizing various aspects differently'. Similarly, Ollikainen (2014, p. 361) has stated that, in the context of the forest sector, BE is 'an integral part of the green economy but do not exhaust the idea'. Loiseau et al. (2016) also identifies CE and BE as subordinated to GE.

All three concepts can be considered limited in that they largely embrace the idea of economic growth, as also pointed out for instance by Tomaselli et al. (2017); Kitchen and Marsden (2011); Murray et al. (2015). Notably, it may be that none of the three concepts (CE, GE and BE) are in fact embedded in strong sustainability since according to several scholars, unlimited growth cannot be reconciled with strong sustainability (e.g. Alier, 2009; Lorek and Fuchs, 2013). According to a conceptual analysis by Loiseau et al. (2016) BE is the least of the three concepts to identify with strong sustainability, while CE and GE are considered more oriented towards strong sustainability. Based on our analysis CE is generally associated with relative decoupling and thus weaker sustainability. However, Martins (2016) has recently argued that in the classical understanding and framing of CE there is space for strong (environmental) sustainability ideas, e.g. irreversibility of natural resources. In our results, we also find that BE can be framed between the narratives of relative decoupling and green growth. Pülzl et al. (2014, p. 391) have suggested that BE 'interweaves arguments of doom (limits to growth) with technological arguments (ecological modernisation) and economic arguments (neoliberalism),[12] while being concerned mostly about the economy'. Hausknost et al. (2017) have proposed a conceptual model hypothesising four directions for BE based on the following categories: industrial/biotechnology vs agroecology -oriented; growth-seeking vs socio-economic sufficiency or degrowth.

Synergies among the three concepts are found in the way they can supplement each other. Given the more international context, GE may be considered as an umbrella concept, which is appropriating concepts from the other concepts (as also assumed in Loiseau et al., 2016). For example, within GE, clean technology is also an important component (Eaton, 2013), with e.g. renewable energy, and sanitation solutions in developing countries. While GE has already incorporated key aspects of BE and CE, the latter two do not show concrete links to each other on a macro-level. Several scholars have recently advocated for an integration of CE principles in BE. Allen (2016) argued for a 'circular bioeconomy' to ensure that BE truly delivers resource efficiency. In the context of the forest sector, this idea is currently being explored at the EU level with the cascading use of wood (Ciccarese et al., 2014; Vis et al., 2016). This principle applies the CE idea of waste hierarchy to biomass

[10] Several authors have pointed out the limits of eco-efficiency (Franceschini and Pansera, 2015; Gladwin et al., 1995; Korhonen and Seager, 2008). The main criticism to eco-efficiency is that improvements in material and energy utilization do not address, and may actually encourage increasing consumption. Eco-efficiency is in this sense limited to a 'depletive' kind of thinking, rather than 'sustaining, restorative and regenerative' solutions (Young and Tilley, 2006, p. 403–404).

[11] Notably, part of the BE literature emphasises the role of science-based knowledge generation, which can be considered cultural services; and the concept of biosecurity, which includes also regulating services.

[12] For example, nature and information commodification, as also argued by Birch et al. (2010).

resources (Bezama, 2016), by a prioritization of higher value uses of wood (e.g. biomaterials) before energy production.[13] Critical literature is also needed about different BE visions and their role and impact on broader natural capital, biodiversity and ecosystem services, as suggested by Marchetti et al. (2014) and Székács (2017). Similarly, the idea of nature-based solutions from GE concept (Ten Brink et al., 2012) could be integrated in the discussion on CE. Scientific or grey literature on the matter is however largely absent.

Ultimately the three concepts represent an opportunity and the ambition to transition economies to a more sustainable trajectory. Since the concept of GE seems to be the most inclusive candidate (Kettunen and Ten Brink, 2015), it could be valuable to integrate some GE ideas into the design and operation of BE and CE. Considering these concepts as complementary, rather than as isolated and competing, can be beneficial as it contributes to inclusiveness. However, since the three concepts may contain fundamentally conflicting elements, it is important not to overemphasise the relative role of the different concepts, but rather the concrete actions and their verified impacts. Such inter and intra diversity of the concepts can in fact lead to different sectors preferring a certain concept or conceptualization within that concept, which can dictate the further evolution and practical uptake, risking narrowing down or even altering the original proposition.

5. Conclusions and the way forward

Despite their evidently different assumptions and operationalization strategies, the concepts of Circular, Green and Bio economy (CE, GE, BE) are joint by the common ideal to reconcile economic, environmental and social goals. In the past decade, they have all gained political interest, coming to exercise great influence on several societal actors and their activities, including for instance industries, academia, NGO's and policy makers. This phenomenon implies that multiple actors are involved in CE, GE and BE conceptualisations, which are thus bound to be internally diverse. Furthermore, various actors adopt or dismiss these guideline concepts as they gain or lose momentum, or as they can legitimise or hamper their interests and activities.

A critical comparison of CE, GE and BE potential and limits, currently missing, would provide important basis to further inform, among others, research and policy implementation. To address these issues, this article aimed at: 1. identify the diversity within and between CE, GE and BE, based on the temporal and geographical distribution and content analysis of the relevant literature; 2. identify CE, GE and BE positions in respect to six sustainability narratives, and their emphasis on different sustainability aspects (environmental, social). Using a machine learning-based analysis, we reviewed close to two thousand scientific articles dealing with CE, GE and BE literature. Our review is limited to scientific research published in English.

The results show that the three concepts have different geographical distributions, with Chinese dominance in CE research, a strong European BE focus and a mostly global reach for GE. Content-wise, CE focuses on industrial urban processes for decoupling resource use and economic output; BE focuses on biological resource-based innovation and land use practices in the context of rural development; and GE envelops an umbrella perspective for a balanced social-environmental development with a global research area. We find that GE research is the most inclusive concept, including some ideas from both CE and BE. None of the concepts addresses degrowth topics and thus fail to deal with potential limits to growth.

Our analysis paints a static representation of CE, GE and BE concepts and their contribution to sustainability transitions (Markard et al., 2012), but we do find and acknowledge that such concepts are multi-faceted, plastic and actively evolving. In particular, we record a great internal diversity of the narrative, especially in GE and BE. Notably, such diversity might have effects on the use of the concept in literature, and its value and longevity for building a sustained relevance in the field of study.

Based on our findings, suggestions for future research include the following. 1. The investigation of which CE, GE and BE strategies are promoted in different countries or regions, considering indexed journals as well as policy documents and grey literature in other languages. In particular, it could be worth focusing on the thematic diversity of GE and its regional priorities; GE is, in fact, the most inclusive concept among the three, and widely diffused geographically. 2. The analysis of CE, GE and BE evolution over time, and their reciprocal influence (cf. sustainability journeys, Garud and Gehman, 2012). A related aspect to be discussed regards the characteristics that have contributed to the successful popularisation and implementation of the three concepts. 3. The further analysis of synergies and limits among CE, GE and BE and possibly the harmonization of their divergences.

At policy level, there is need to 1. Refine, clarify and systematize contemporary concepts, without denying their intrinsic diversity; promoting the more integrated interpretation and applications of CE, GE and BE as a way to enhance effectiveness towards common sustainability goals; identify opportunity areas and related societal actors to pursue the merging of multiple concepts in light of their synergies and conflicts. 2. Enriching and improving the overall landscape of policy instruments implementing these concepts (Rogge and Reichardt, 2013), with particular attention to the efficacy, efficiency and consistency.

Acknowledgements

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Appendix

Figs. 8–10 included in the appendix are a snapshot of the results from the LDA analysis used in the study. The results are interactive and can be best explored at the following website: http://www.ufz.de/index.php?en=42249. Each figure includes six diagrams (a-f), one for every topic identified in the corpus. The scatterplot on the left side of each diagram represents the linguistic distance among the six topics identified in the corpus. The topics are represented in the scatterplot as circles; the circles' size indicates the topic's marginal distribution. For example, the scatterplot in Fig. 8a highlights the position of topic 1 within CE literature (note, the circle numbered 1 is highlighted in red). On the right side of the scatterplot, the most salient keywords for topic 1 are listed. Further information on the LDA analysis can be found in section 2.1.

[13] This cascade principle is not without problems, as ranking is highly dependent on end use prices that tend be dynamic (Hetemäki, 2014).

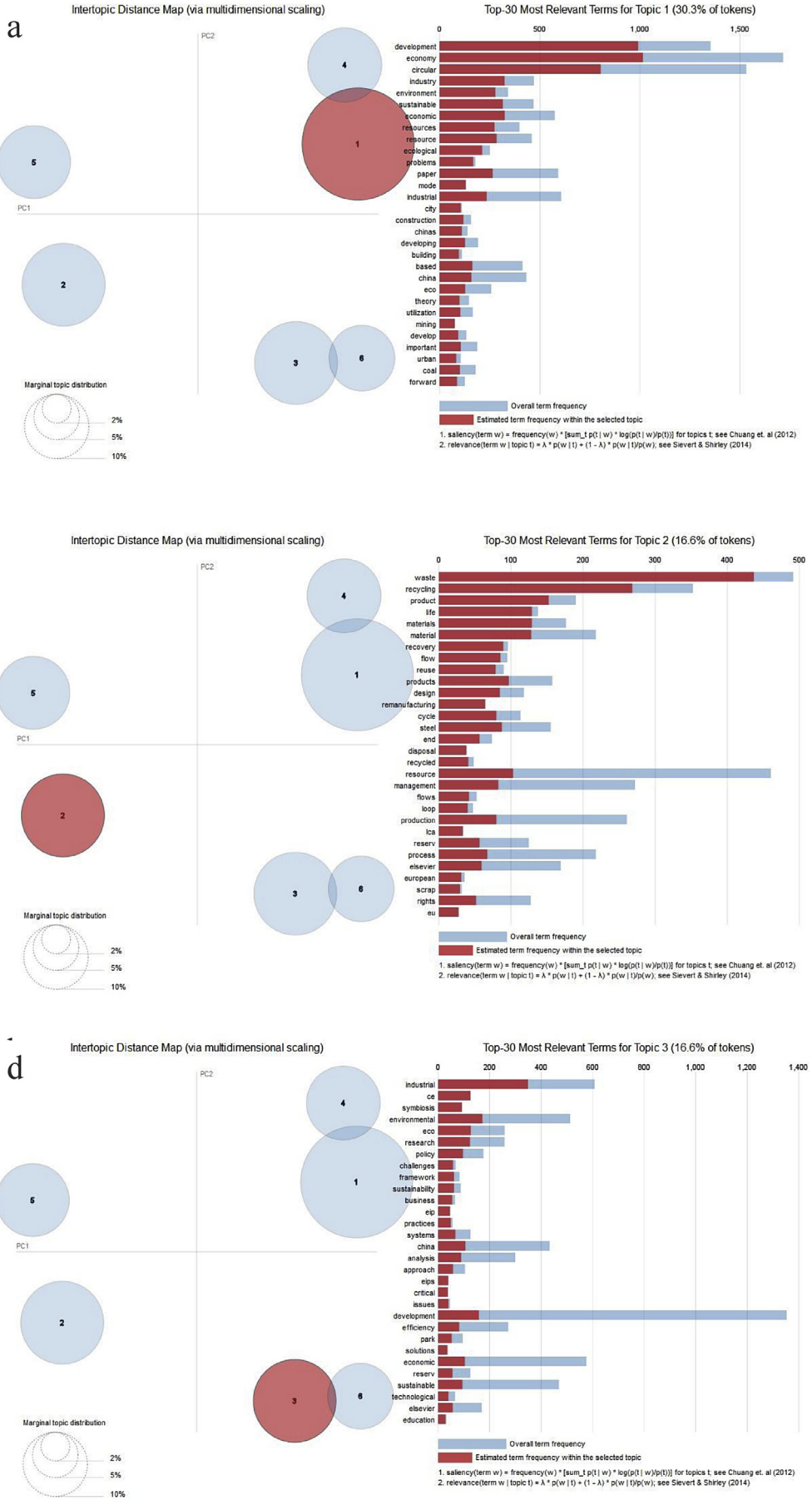
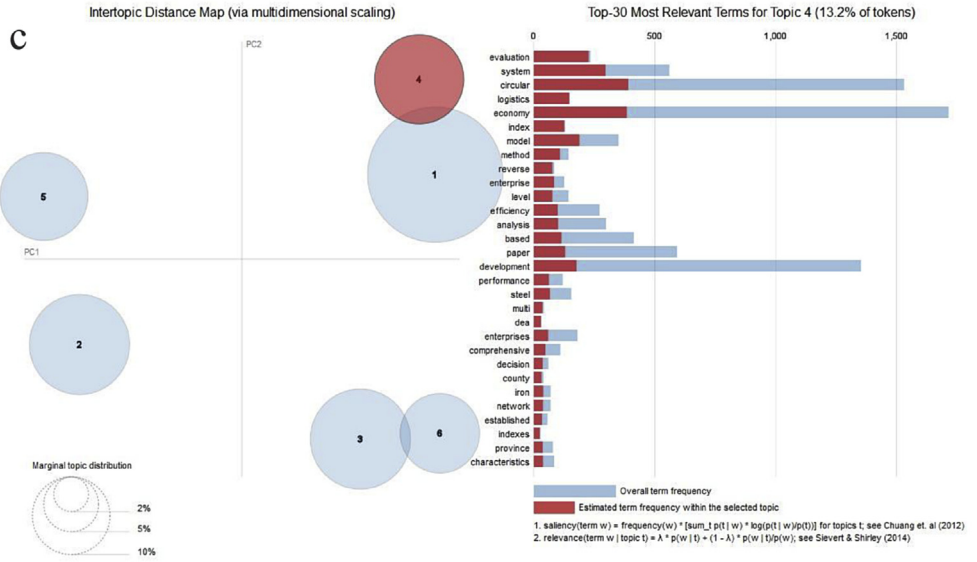
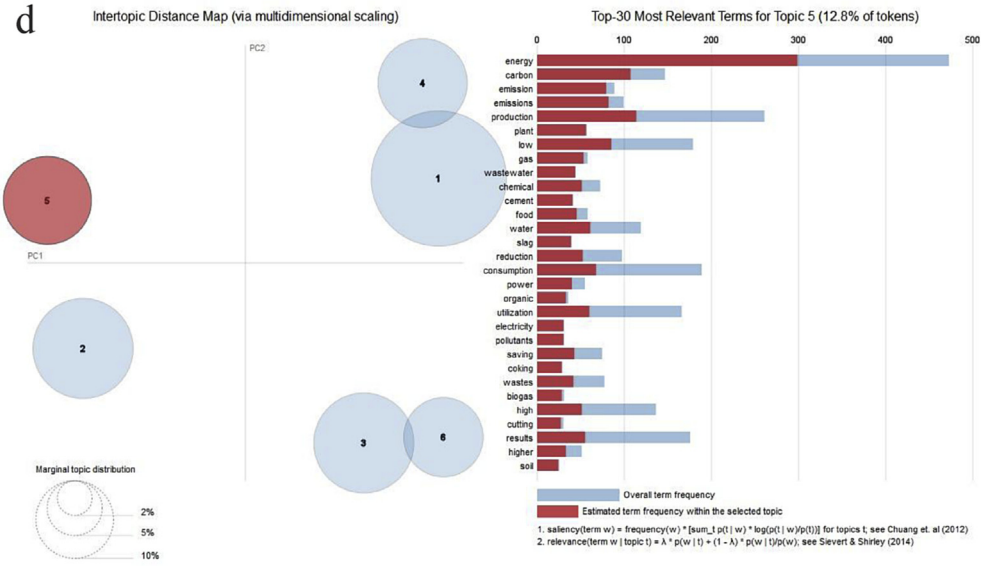


Fig. 8. Topic analysis (1-6) for CE concept.





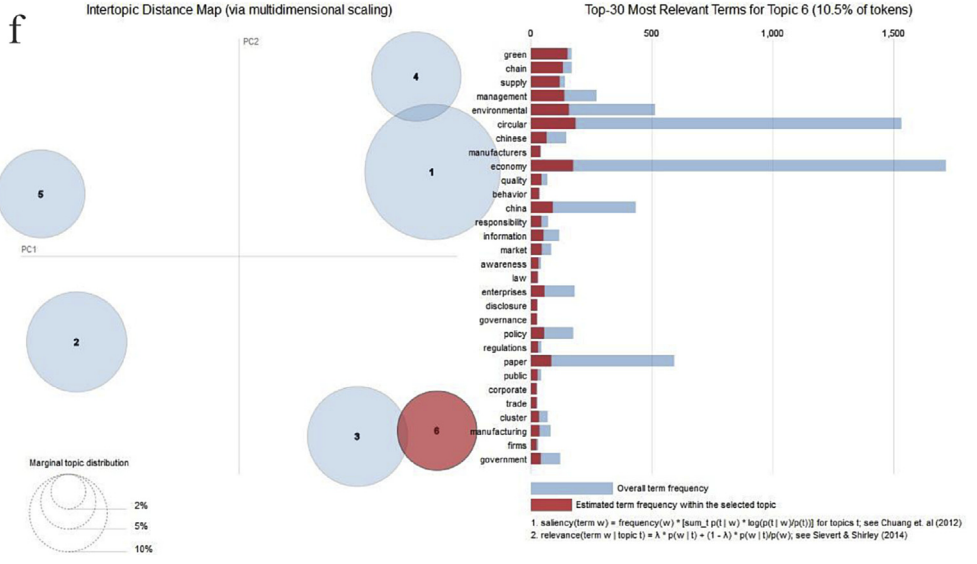


Fig. 8. (*continued*).

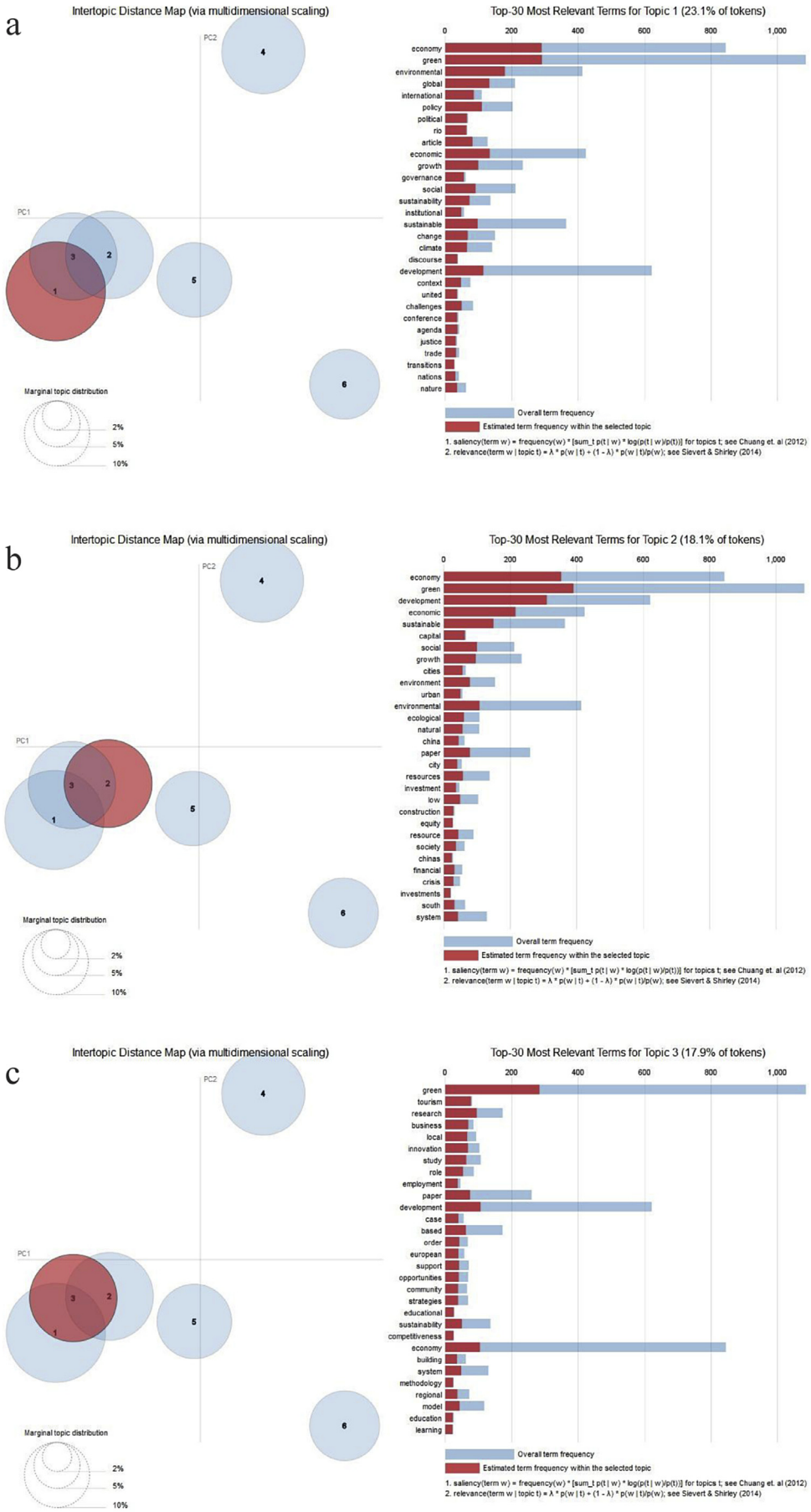
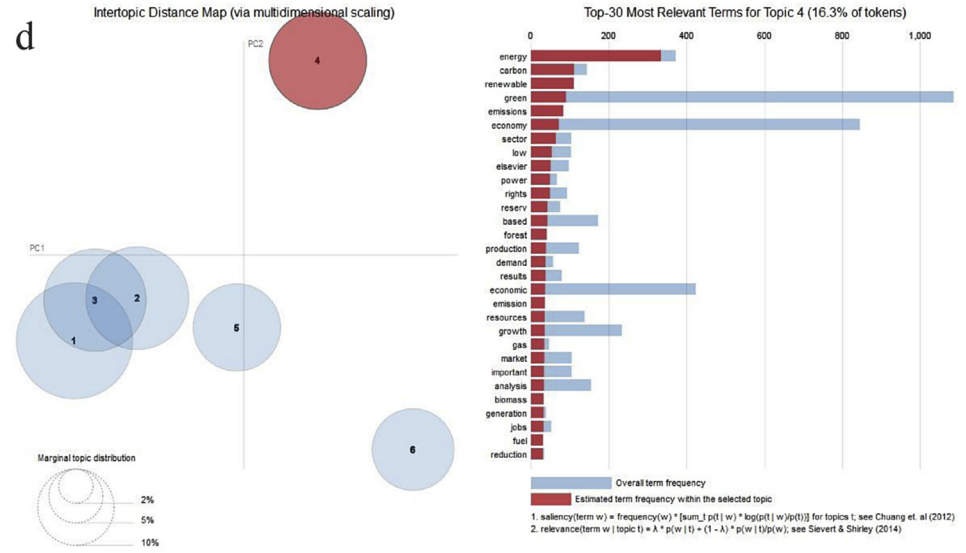
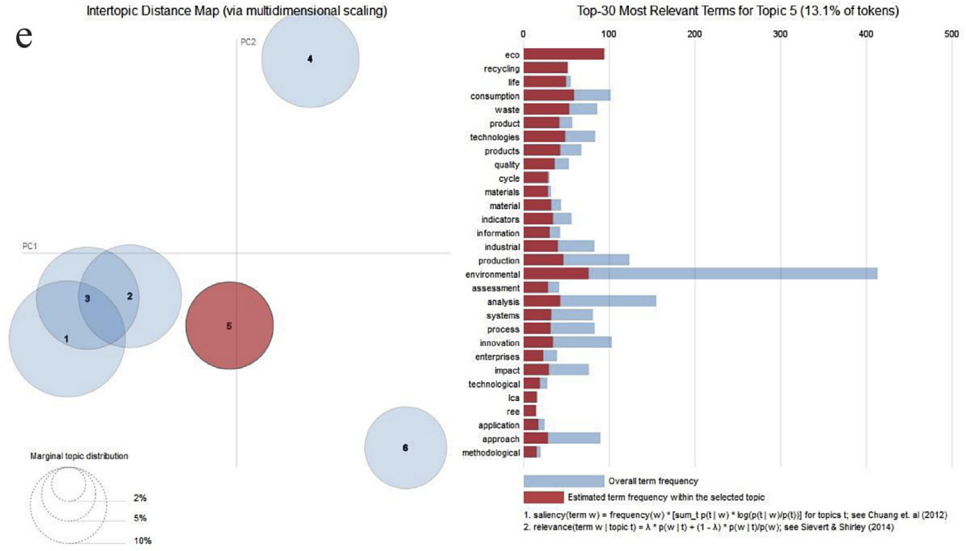


Fig. 9. Topic analysis (1-6) for GE concept.





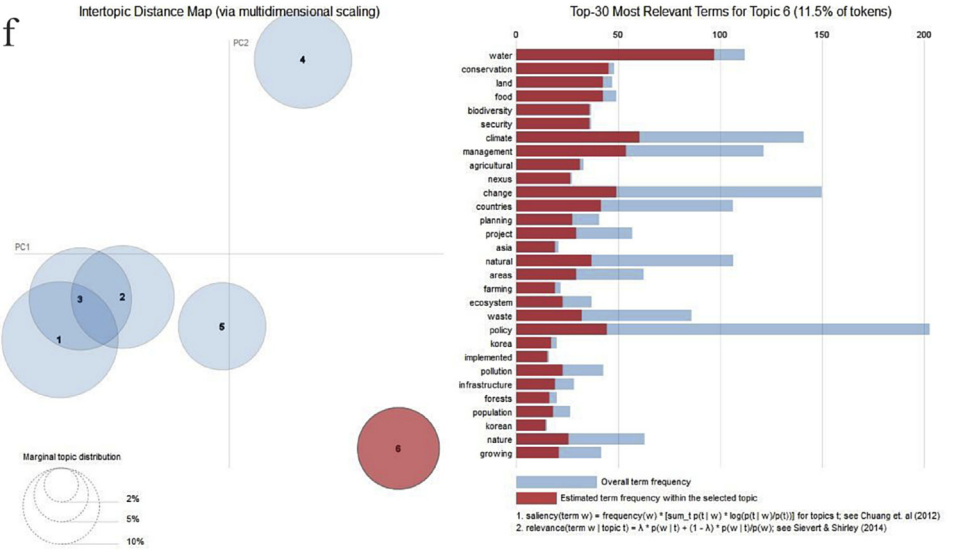


Fig. 9. (*continued*).

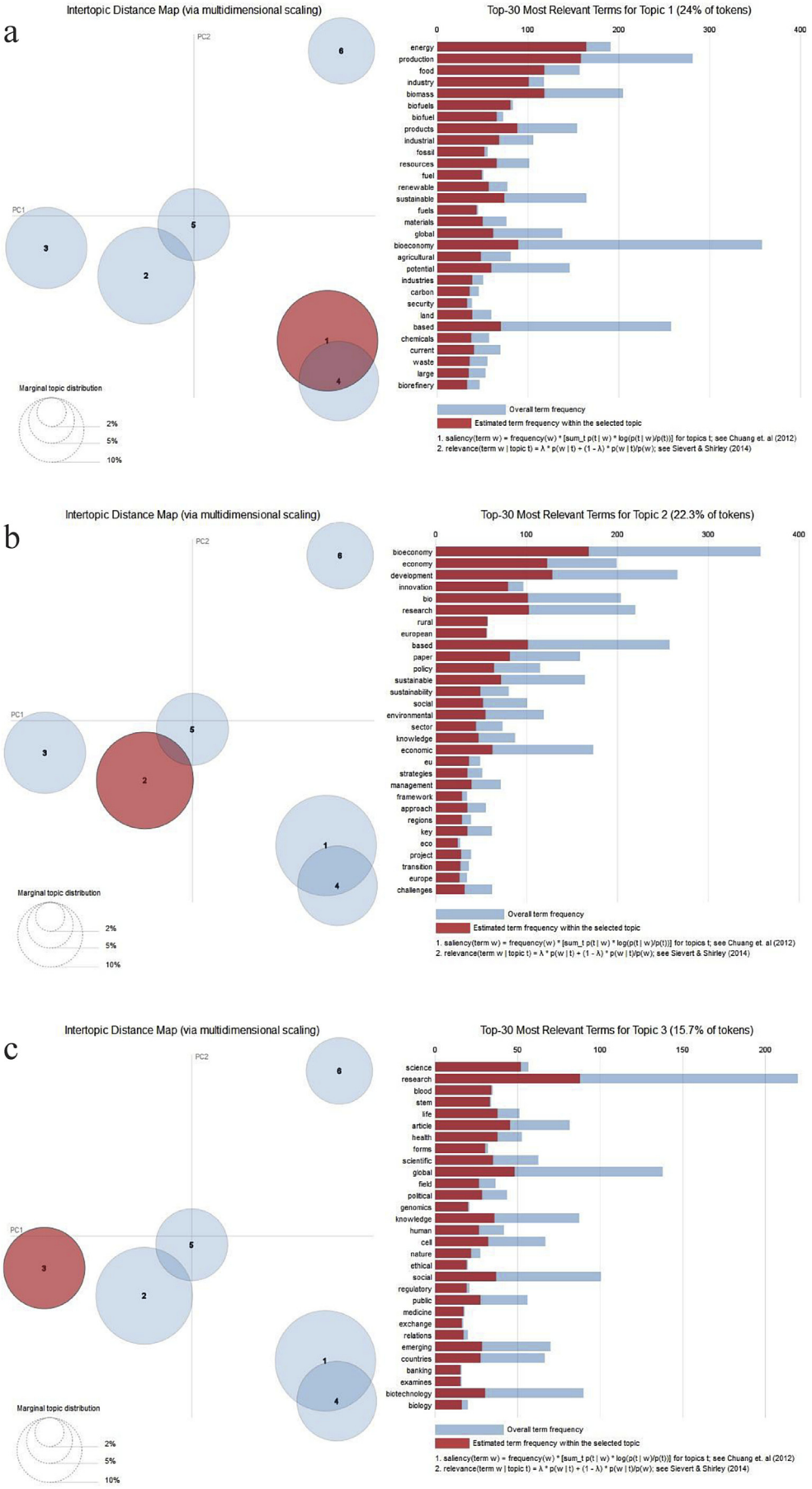
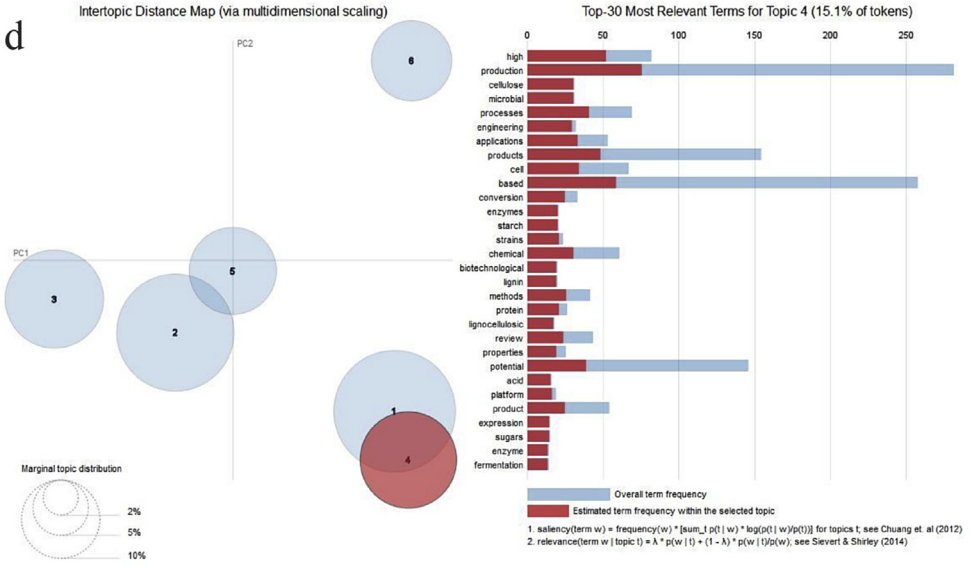
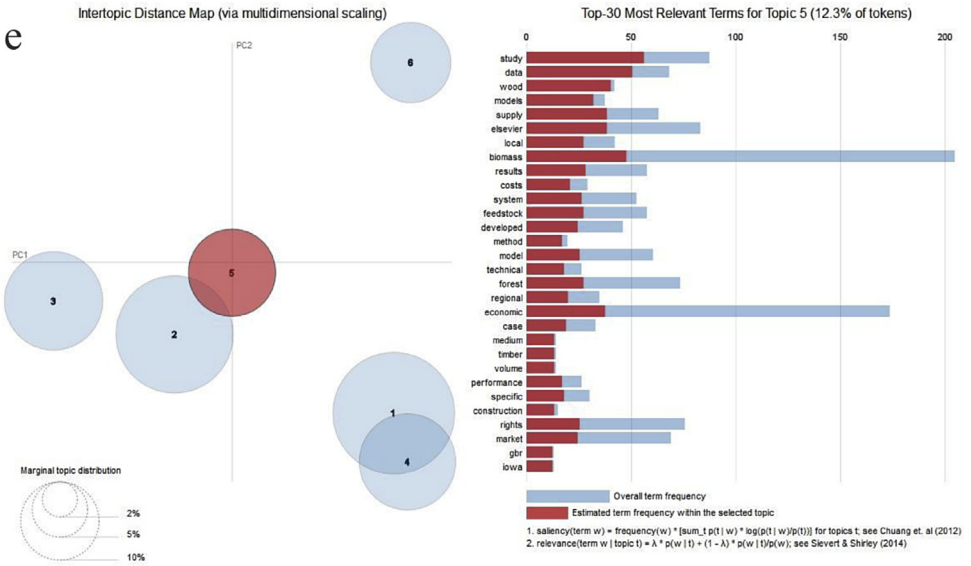


Fig. 10. Topic analysis (1-6) for BE concept.





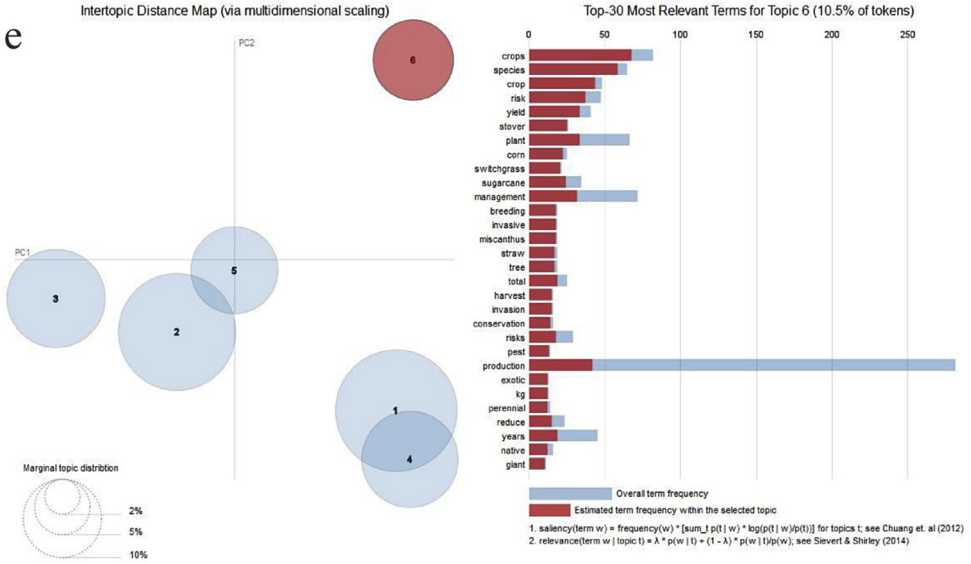


Fig. 10. (*continued*).

Table 7
Definitions for technical terminology occurring in the article.

Term	Definitions
Corpus	A collection of text that is analysed.
Token	Meaningful element of the text, after separation from spaces, punctuation, acronyms, numbers, hyphens or other symbols.
Salience	Keywords frequency in the corpus.
Relevance	Ratio of the keywords frequency in a certain topic to the frequency in the corpus.
Sustainability narrative	Storylines characterised by problem definition, consequences identification and solutions seeking. In this process of problem solving, narratives imply prioritization of some practices and actors. Franceschini and Pansera (2015) identified six sustainability narratives.
Sustainability dimension	Sustainability dimensions include economic, social and environmental.

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