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Abstract

Generating negative emissions by removing carbon dioxide from the atmosphere is a key requirement for limiting global warming to well below 2 °C, or even 1.5 °C, and therefore for achieving the long-term climate goals of the recent Paris Agreement. Despite being a relatively young topic, negative emission technologies (NETs) have attracted growing attention in climate change research over the last decade. A sizeable body of evidence on NETs has accumulated across different fields that is by today too large and too diverse to be comprehensively tracked by individuals. Yet, understanding the size, composition and thematic structure of this literature corpus is a crucial pre-condition for effective scientific assessments of NETs as, for example, required for the new special report on the 1.5 °C by the Intergovernmental Panel on Climate Change (IPCC). In this paper we use scientometric methods and topic modelling to identify and characterize the available evidence on NETs as recorded in the Web of Science. We find that the development of the literature on NETs has started later than for climate change as a whole, but proceeds more quickly by now. A total number of about 2900 studies have accumulated between 1991 and 2016 with almost 500 new publications in 2016. The discourse on NETs takes place in distinct communities around energy systems, forests as well as biochar and other soil carbon options. Integrated analysis of NET portfolios—though crucial for understanding how much NETs are possible at what costs and risks—are still in their infancy and do not feature as a theme across the literature corpus. Overall, our analysis suggests that NETs research is relatively marginal in the wider climate change discourse despite its importance for global climate policy.

Introduction

Negative emissions technologies (NETs) have received growing attention in science and policy. The new long-term climate goals of the recent Paris Agreement are associated with tight and fast dwindling carbon budgets, suggesting a rapidly-increasing dependence on NETs in order to compensate for the lack of substantive short term emission reduction commitments by countries (Minx *et al* 2016). The most recent Fifth Assessment Report (AR5) by the Intergovernmental Panel on Climate Change (IPCC) prominently highlighted the important, but varying role that NETs—in particular bioenergy in combination with carbon capture and storage (BECCS)—play in 2 °C scenarios (Clarke *et al* 2014, IPCC 2014). This kicked-off a controversial debate that focused on the feasibility of climate change mitigation pathways that involve large amounts of NETs (Fuss *et al* 2014, Anderson 2015, Geden 2015, Vaughan and Gough 2016).

The Paris Agreement not only sets out countries' intention to limit global mean temperature rise well-below 2 °C, but also to actively pursue efforts to keep further warming at 1.5 °C below pre-industrial levels (United Framework Convention on Climate Change 2015). This strengthening of mitigation ambition has further raised the importance of NETs in climate

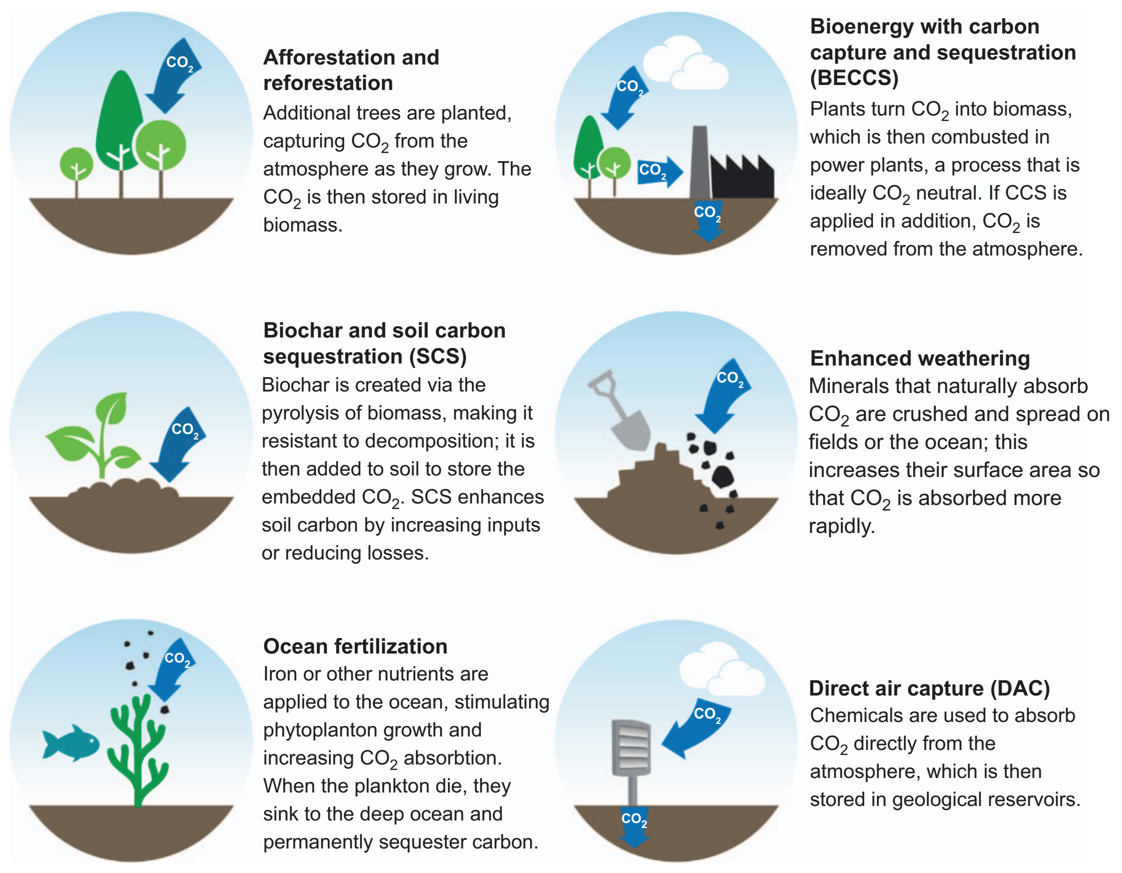

Figure 1. Different groups of negative emission technologies exist. Some are rather recent innovations while others have been practiced already for centuries. Note that this list is not exhaustive, in particular it excludes a technology that has recently entered the debate: 'blue carbon' (see Johannessen and Macdonald 2016).

policy. The close-to-zero remaining carbon budget requires a large-scale deployment of NETs in order to pull temperatures back below the 1.5 °C threshold by 2100 (Luderer *et al* 2013, Clarke *et al* 2014, Rogelj *et al* 2015). While there are still scenarios that achieve the 2 °C goal with no or very small deployment of NETs (Minx *et al* 2016, Smith *et al* 2016), the available evidence on the 1.5 °C goal highlights the requirement to deploy large amounts of NETs to sequester 400–1000 Gt CO_2—equivalent to between 10 and 25 years of CO_2 emissions at current rates (Luderer *et al* 2013, Rogelj *et al* 2015).

Hence, NETs will play a prominent role in the new special report on the 1.5 °C goal the IPCC is currently preparing as a scientific input to the global stock-take in international climate policy negotiations in 2018. The treatment of NETs will need to go beyond what has been done for AR5, which has largely centered around evidence from long-term mitigation scenarios (Clarke *et al* 2014). The integrated scenario literature—with some notable exceptions (Keith *et al* 2006, Wise *et al* 2009, Chen and Tavoni 2013, Humpenöder *et al* 2014, Kreidenweis *et al* 2016)—has largely focused on removing carbon dioxide from the atmosphere by means of bioenergy in combination with carbon capture and storage (BECCS). But there are many other routes for extracting CO_2 from the atmosphere that have not been comprehensively treated by the IPCC so far (see figure 1).

The broader literature on NETs so far seems to suggest that all NETs have stark limits (e.g. The Royal Society 2009, Vaughan and Lenton 2011, McLaren 2012, Smith 2016, Smith *et al* 2016): some are currently hugely expensive while others require large amounts of land and may involve potentially large risks to food security or biodiversity. Prudence suggests that a portfolio of carbon dioxide removal options will be needed, with assessment of each NET underpinned by three important questions: 1) how much; 2) at what costs; 3) at what risks.

Yet, scientific assessments themselves are becoming increasingly challenging. Exponential growth in the climate change literature makes it increasingly hard for individual authors to stay abreast of developments in a particular field (Grieneisen and Zhang 2011, Haunschild *et al* 2016, Minx *et al* 2016). Systematic reviews—meta-analyses that apply formal research methods to study research results—are becoming increasingly important to a) ensure adequate progress in accumulating knowledge in the field; b) avoid systematic omissions of the literature; c) transparently inform policymakers about the state of science; and d) secure the long-term credibility of scientific assessments themselves (Petticrew and McCartney 2011, Berrang-Ford *et al* 2015, Minx *et al* 2016).

In this paper, we use scientometric approaches to gain an overview of the development of negative emissions research over the past three decades. We develop a transparent search query to discover a body of publications that addresses NETs; and apply a topic model algorithm to systematically digest the underlying themes contained in these papers (in lieu of the monumental task of manually analyzing such a large corpus). To our knowledge this is the first application of topic modelling to understand the thematic structure of a particular scientific field in climate change research.

Methodology

Scientometric methods (Leydesdorff and Milojević 2015) have been increasingly applied to analyze the structure, evolution and contributions to the field of climate change research (Stanhill 2001, Grieneisen and Zhang 2011, Li *et al* 2011, Haunschild *et al* 2016). We add to discussions on the topic of NETs (Belter and Seidel 2013, Oldham *et al* 2014) by expanding the temporal coverage of existing research and by including a more exhaustive list of technologies.

The data for this analysis is derived from a WoS literature query up to the end of 2016. WoS is a subscription-based scientific citation indexing service that provides a comprehensive citation search. Our search is a combination of eight strings, each comprising one of the NET technologies under study, as well as a group of generic keywords for NET research (note that solar radiation management—SRM—is not part of our query, as this technology does not entail carbon removals from the atmosphere). The search string was built up iteratively to include the relevant synonyms for each technology and to exclude keywords that confounded our results. Throughout this procedure, random samples of the dataset were taken to ensure at least 90% of the queried papers met our standard for inclusion; samples were then independently reviewed and cross-checked for consistency. All document types were included in the search. The entire, comprehensively annotated search query is provided in the supplementary information (SI available at stacks.iop.org/ERL/12/035007/mmedia). To calculate the citation impact of publications we use a common normalization procedure as described in Bornmann and Marx (2015) (see SI). The citation data for the calculations are from an in-house database at the Max Planck Society which is based on WoS.

Given the large amount of information that has accumulated on NETs in a relatively short amount of time, we apply probabilistic topic modelling called Latent Dirichlet Allocation (LDA) to discover the various themes that characterize the body of NETs literature we identified from our search query (Blei *et al* 2003, Blei 2012). LDA generates a list of topics with the words that constitute them at given probabilities, and labels each document with the probability that it belongs to each topic. As the number of topics needs to be specified exogenously, we sample different numbers of topics and analyze the resulting word distributions manually. Overall, 19 topics proved to be a meaningful and manageable number, covering a broad spectrum of themes, while minimizing uninterpretable results. We describe the methodology in more detail in the Supplementary Information.

Results

Our search query identifies a substantive and expanding body of literature on NETs. Figure 2 shows how this literature has developed in the WoS between 1991 and 2016. Overall we find a total of about 2900 publications. This is a considerable amount, but still appears modest compared to the more than 220 000 publications in the broader field of climate change (Grieneisen and Zhang 2011, Haunschild *et al* 2016, Minx *et al* 2016). The number of NETs publications has grown exponentially as well—but kicking off later than in climate change as a whole (only towards the end of 2000's) from extremely low levels. This is because NETs are a rather new topic that only emerged very slowly during the 1990s, when the annual number of publications was no higher than a dozen. Starting from such a low baseline, the NETs literature has grown at an annual rate of 21%, doubling approximately every 3.4 years. In the same period, all climate change literature grew at a rate of 14%, doubling every 5.3 years. By the end of 2016, we observe almost 500 publications annually devoted to NETs across the WoS.

This pattern is reflected in climate change assessments. For instance, the first three IPCC assessments had very little or no literature on NETs to deal with. Unsurprisingly, NETs were practically absent as a topic from these assessments, with no mention in AR1, a relatively limited discussion of geo-engineering proposals (SRM and ocean fertilization) in AR2, but growing engagement in AR3, particularly in the context of enhancing biological carbon sinks (Kauppi *et al* 2001). With increasingly ambitious climate targets and fast-dwindling carbon budgets, the topic of NETs started shaping up as a distinct research field underpinned by a substantial literature during AR4 and AR5. Across these two cycles, about 360 and 1200 articles were published on NETs, respectively. Distinct sections on NETs in the Working Group 1 (Ciais *et al* 2013) and Working Group 3 (Clarke *et al* 2014) AR5 reports reflect the growing importance of the field. For the next IPCC assessments and the special report on the 1.5 °C goal more than 1200 new studies on the topic have already emerged.

Discussions on NETs can be most frequently found in natural science journals with an overall

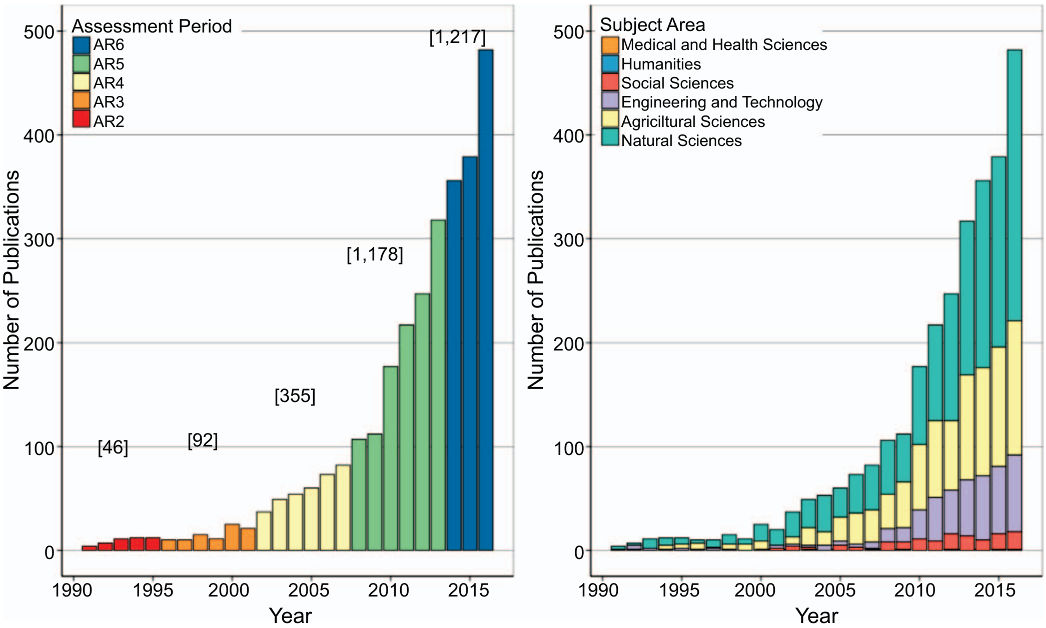

Figure 2. Development of the literature on NETs 1991–2016. The left panel shows the annual number of publications in the Web of Science across the different IPCC assessment periods from the second assessment report (AR2) onwards. The right panel shows annual publications by scientific domain using the OECD Field of Science and Technology classification (OECD 2007).

publication share of about 54% in 2016. However, the dominance of natural science publications is less pronounced than for the climate change literature as a whole where the publication share is about 62%. As many of the key issues on NETs evolve around specific technologies and practices, agricultural science outlets for land-based NETs as well engineering and technology journals for the other NETs are more prominent. The social sciences and humanities are crucial for discussions on implementation, ethics and governance among other issues, but NET discussions have not yet caught on in these fields in the same way as the wider climate change literature. However, there are important caveats to consider: first, interdisciplinary journals like *Science*, *Nature*, or *Nature Climate Change* among others are classified as natural science outlets here, even though they invite pieces from many disciplines. Second, authors from fields without a strong focus on climate change like humanities might choose other outlets—particularly interdisciplinary journals—for their contributions.

Looking at the list of topics predicted by our topic model in table 1, a wide range of themes emerge covering the different scientific, technological, managerial and policy aspects of NETs. Each topic is characterized by a descriptive name, assigned by us on the basis of the key features, and its five most prominent keywords. Note that keywords have been stemmed to combine multiple word that have the same root. Topics towards the top of the table have a higher marginal topic distribution and are more likely to appear in the NET literature.

We find that many of the major groups of NETs are distinct enough to generate their own topic: biochar and charcoal (1, 14), reforestation (3), air capture (6), afforestation (9) and blue carbon (11). Ocean fertilization and enhanced weathering (15) are clustered into a single topic due to the semantic and technical similarities between these two processes. Soil carbon management is picked up across a wide range of topics (2, 7, 12, 16, 19). BECCS is represented in terms of its energy-generation and CCS components in the energy economics topic (4). This topic (4) also contains the integrated assessment literature, where the potential importance of NETs for meeting the international climate policy goals has been consistently raised.

We further find that some of the topics may relate to groups of technologies, or the NET field as a whole. For instance, the institutions and governance (8) topic addresses key implementation issues for a variety of land and marine-based NETs, while microbial communities (16) or wood harvesting (19) are specific topics in the context of biochar and forest-based NET discussions, respectively. Geoengineering (13) reflects a higher-level discourse on earth-system responses (such as radiative forcing) and seems to also capture SRM techniques, which were not part of our search query, but were included due to the widespread use of ‘geoengineering’ as a ‘catch-all’ term for large-scale climate interventions in the NET literature.

Figure 3 visualizes the topics in a force-directed graph of inter-topic correlations. It identifies which topics are closely associated with one another, based on their likelihood to appear together in the same paper. For instance, the more a paper is associated with energy economics (4), the more likely it is also to be associated with bioenergy and lifecycles (18), since these topics are highly correlated. Accordingly, we observe a noticeable cluster of topics around energy

Table 1. List of estimated topics and their keywords. The top 5 keywords for each topic are ranked according to their frequency-exclusivity score (Sievert and Shirley 2014). The marginal topic distribution denotes the proportion of the corpus that each topic represents. This measure does not necessarily describe the proportion of papers devoted to a given topic—since papers are combinations of topics—however topics with a higher distribution are certainly more likely to appear in the corpus.

ID	Topic name	Stemmed keywords	Marginal topic distribution
1	Biochar	biochar, amend, pyrolysi, feedstock, incub	8.7%
2	Grassland and cropland	soc, grassland, stock, cropland, china	7.5%
3	Reforrestation	forest, reforest, china, tropic, deforest	7.1%
4	Energy economics	energi, technolog, captur, ccs, power	7.0%
5	Forest carbon sequestration	tree, speci, stand, root, litter	6.6%
6	Air capture	captur, air, adsorpt, materi, adsorb	5.8%
7	Land-use scenarios	scenario, project, cost, price, forestri	5.6%
8	Institutions and governance	polici, market, protocol, kyoto, intern	5.4%
9	Afforestation	afforest, plantat, stock, pine, layer	5.2%
10	Trace-GHGs	ha1, n2o, yr1, pastur, flux	5.0%
11	Blue carbon	servic, restor, mangrov, coastal, habitat	4.4%
12	Soil enhancement	treatment, residu, miner, rice, straw	4.3%
13	Geoengineering	optim, terrestri, radiat, forc, centuri	4.3%
14	Charcoal	degre, stabil, char, charcoal, decomposit	4.3%
15	Ocean fertilization and enhanced weathering	ocean, iron, weather, releas, day	4.2%
16	Microbial communities	communiti, microbi, dri, abund, group	4.2%
17	Agroforrestry	farm, biodivers, food, agroforestri, program	3.6%
18	Bioenergy and lifecyles	ghg, bioenergi, biofuel, energi, life	3.4%
19	Wood harvesting	harvest, rotat, wood, simul, ton	3.4%

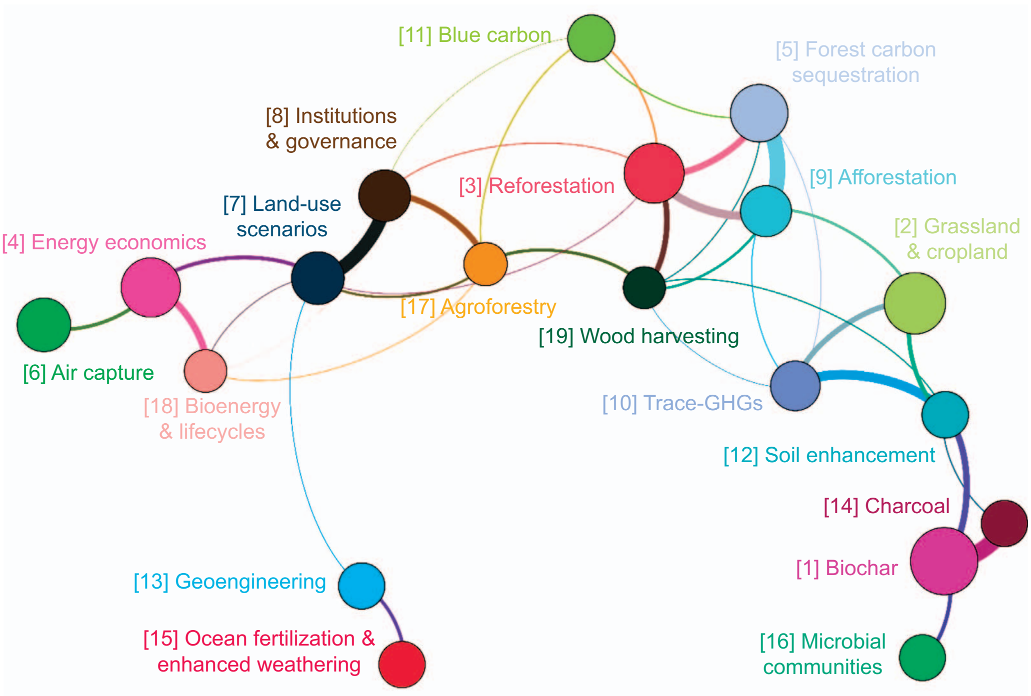

Figure 3. Correlation structure of negative emissions topics. Each node represents a topic, scaled by the marginal topic distribution (table 1); each line represents a positive correlation between two topics. The largest correlation is of 0.24 between biochar and charcoal. Nodes that are proximate to one another are more highly correlated than those which are distant. The visualization is generated from inter-topic correlations using the force-directed algorithm ForceAtlas2 in Gephi (Jacomy *et al* 2014).

economics, bioenergy and lifecycles, and air capture (4, 18, 6). A second cluster forms around forest themes (3, 5, 9, 17, 19) to which also blue carbon (11) is connected as a substantial part of the literature is concerned with mangrove forests. Both clusters are linked through the land-use scenarios (7) and institutions and governance (8) topics. A final cluster can be found around biochar and non-forest soil carbon themes (1, 2, 10, 12, 14, 16).

The positioning of policy-based discourses within the NETs literature landscape largely fits our expectations: land-use scenarios (7) is proximate to the cluster of energy-systems topics and tends to be focused on regional or global economic modelling and scenarios

Table 2. Top 10 publications on negative emissions technologies by normalised citation score. Topic keywords with a probability score of at least 0.2 are included for each paper; keywords in bold are highly probable, with a threshold of 0.3.

	Publication	Title	Journal	Score	Topic keywords
1	Meinshausen *et al* 2011	The RCP greenhouse gas concentrations and their extensions from 1765 to 2300	CLIMATIC CHANGE	40,66	**Geoengineering, Land-use scenarios**
2	Post *et al* 2000	Soil carbon sequestration and land-use change: processes and potential	GLOBAL CHANGE BIOLOGY	26,91	**Grassland and cropland**
3	Zimmerman *et al* 2011	Positive and negative carbon mineralization priming effects among a variety of biochar-amended soils	SOIL BIOLOGY & BIOCHEMISTRY	26,62	**Biochar**
4	Canadell *et al* 2008	Managing forests for climate change mitigation	SCIENCE	23,62	**Reforestation**
5	Keiluweit *et al* 2010	Dynamic Molecular Structure of Plant Biomass-Derived Black Carbon (Biochar)	ENVIRONMENTAL SCIENCE & TECHNOLOGY	22,07	**Charcoal**
6	Jones *et al* 2012	Biochar-mediated changes in soil quality and plant growth in a three year field trial	SOIL BIOLOGY & BIOCHEMISTRY	21,29	**Biochar, Microbial communities**
7	Chan *et al* 2007	Agronomic values of greenwaste biochar as a soil amendment	AUSTRALIAN JOURNAL OF SOIL RESEARCH	20,66	**Biochar**
8	Schimel *et al* 1994	Climatic, edaphic, and biotic controls over storage and turnover of carbon in soils	GLOBAL BIOGEOCHEMICAL CYCLES	20,22	**Geoengineering**
9	Donato *et al* 2011	Mangroves among the most carbon-rich forests in the tropics	NATURE GEOSCIENCE	19,66	**Blue carbon, Reforrestation**
10	Snyder *et al* 2009	Review of greenhouse gas emissions from crop production systems and fertilizer management effects	AGRICULTURE ECOSYSTEMS & ENVIRONMENT	19,01	Bioenergy and lifecycles

('scenario', 'projection', 'cost', 'price'); whereas institutions & governance (8) sits closer to the forestry cluster and is primarily focused on implementation issues ('policy', 'market', 'protocol'). Intuitively, this reflects well the different policy concerns and requirements of nascent technology-based NETs (BECCS and air capture) versus conservation and management based NETs (reforestation, blue carbon management), the latter of which by now has accumulated a large body of implementation studies. Notably, biochar (1) has no correlating policy-focused topic (and thus remains predominantly technical in scope), while ocean fertilization and enhanced weathering (15) are only weakly related to land-use scenarios (7) via the geoengineering topic (13).

Looking at topics that have few correlations, it is evident that ocean fertilization and enhanced weathering (15) and geoengineering (10) are in fact highly disconnected from the overall topic space. In other words, the papers that are strongly associated with these topics do not have a tendency to be systematically associated with other individual topics. However, they are closely connected to one-another (and therefore also to SRM, which features prominently in the geoengineering keywords). Of course, these papers may reference other topics and technologies in the main body of their texts (or via citations); but this analysis does show that the semantic content of their abstracts, titles and keywords are internally consistent and relatively homogenous in relation to the other literature analyzed here.

We now turn to the highest impacting publications in the NET corpus, shown in table 2. The first, highest ranking paper is by Meinshausen *et al* (2011), a paper that does not focus on NETs, but describes the long-term Representative Concentration Pathways (RCPs) (see Moss *et al* 2010, IPCC 2013). This includes a characterization of the most ambitious RCP2.6 scenario in terms of negative emissions. All nine other papers in the top-ten ranking focus on land-based NETs, none on energy-systems or ocean-based NETs. Within these, biochar emerges as a highly impacting field, followed by soil carbon management—even once the differences between citation cultures of subject areas have been accounted for.

As a further validation step for the topic model, high ranking papers are tagged by their most probable topics. In most cases, these tags correspond to the content in question (an exception is paper #1, which was tagged as geoengineering due to the prevalence of language around radiative forcing, but also correctly identified as a paper that considers changes in global land-use—i.e. land-use scenarios). Most interesting are the topics excluded from this ranking, such as ocean fertilization and enhanced weathering, energy economics, or indeed broader surveys of the NET field (i.e. papers that combine more than one technology type, or have a diversity of topics). For completeness, we provide a full list of publications analyzed in this paper, including their normalized citation scores and probable topic associations in the supplementary data file. Within the technology specific topics, highest ranking papers tend to be a fairly even split between two broad types: those that have a narrow technology-related focus, dealing with innovations, procedures, costs and so forth; and those that relate NETs to an overall goal of global climate change mitigation. Within the policy-discourse topics—institutions and governance, land-use scenarios—the high ranking papers are very diverse in subject matter, covering a wide range of normative, economic, and policy-based issues in NET research.

Discussion

How much NET potential is available at which costs and risks is fundamental to our understanding of whether and how the climate goals—particularly the 1.5 °C goal—of the Paris Agreement can be met. Establishing a comprehensive overview of the scientific knowledge on the potential, costs and risks of individual NETs will therefore be a key issue for upcoming scientific climate change mitigation assessments. In times of a fast-growing literature base this is a challenge that requires the application of computational tools and methods to track progress in the field; accordingly, this paper sets out to systematically characterize the size, composition, development and topic structure of the available scientific knowledge on NETs, as recorded in the WoS.

The literature on NETs is expanding more rapidly than the field of climate change as a whole. Yet, given its potential importance for meeting the international climate goals, it may be argued that it still does not feature very prominently in climate change research as a whole: just over 1% of the most recent climate change literature (2015)—380 of about 30 000 studies—address NETs. Overall, we find a total of about 2900 publications in the WoS. The exact size of the literature corpus depends on purpose of the analysis and chosen exclusion criteria. Our search strategy is more comprehensive and generous than in previous scientometric work on NETs (Belter and Seidel 2013, Oldham *et al* 2014): we include more technologies and do not add further exclusion criteria in a process of hand-selecting articles (a procedure that would diminish reproducibility). As a result, the literature body identified here also comprises publications that do not primarily focus on NETs, but do give the issue importance, to the extent that they refer to some variation of carbon dioxide removal in title, keywords or abstract directly. Arguably, such publications are relevant as they add to a broader understanding of negative emissions, including the wider co-benefits or risks of NET options that are essential for a comprehensive scientific assessment.

Our search query can be considered as restrictive as well. It would be straightforward to argue that any article that deals with a particular NET—even if not exclusively focusing on the carbon removal aspect—is relevant. For example, by restricting the literature to a mentioning of CO_2 removal we exclude more than 2700 additional publications only on biochar. These excluded studies could contain relevant non-removal aspects of biochar or any other NET option that are essential for a comprehensive biochar evaluation. We argue that our query provides a reasonable trade-off between a focus on NETs in their core capacity as carbon removal technologies and a comprehensive coverage of wider technology aspects.

The identified literature corpus is further restricted to the coverage provided by the WoS. Even though the WoS is relatively comprehensive, but it is by no means exhaustive—even in terms of the peer-reviewed scientific literature. Hence, there are additional journal articles not recorded in the WoS, but also a constellation of government, industry, NGO reports as well as working papers that are of direct relevance to scientific assessments (IPCC 2013). A wider search of this literature could, for example, be undertaken in Google Scholar, but the restrictive result provisioning policy on this platform makes such an analysis cumbersome. We therefore follow the practice of most scientometric studies to focus on the comprehensive, but non-exhaustive coverage by WoS.

While for the very early IPCC assessments a literature on NETs was practically non-existent, in the few years since AR5 there have already been more than 1200 new published studies relevant for AR6. Synthesizing this evidence into policy-relevant knowledge is itself becoming a growing challenge that requires an increasing application of meta-analytical tools (Petticrew and McCartney 2011, Berrang-Ford *et al* 2015, Minx *et al* 2016). It is crucial for scientific rigor and integrity in this process to establish transparency over why studies have been included and others not. As is common practice in any form of meta-analytical work, we provide full details over the search query that is the basis of our findings, so that other studies can critique, replicate, or expand upon these results. Further, a systematic review and evidence gap analysis that determines the state-of-knowledge and open research questions on NETs is currently not available and urgently required.

We apply topic analysis—to our knowledge for the first time—in the field of climate change to get a better understanding of the thematic structure of the NET discussion. NETs are usefully reflected in the topic structure—some as an individual topic, others across several topics and others nested within a topic (such as BECCS). Some topics refer to a literature that is global and cross-sectoral in scope, while others relate to technology- or project-specific studies that require different means of scientific assessment.

Our topic analysis suggests a current separation in the NET literature into three clusters around energy-systems, forestry and other land-based methods. The absence of a cross-cutting themes relating to considerations of entire portfolios of NET options and connecting the different research themes is striking, but seems to well-reflect the structure of the research field. This divide is, for instance, mirrored in the existing scenario literature, where in almost all scenarios analyzed for the last IPCC report BECCS was the only NET option available (Fuss *et al* 2014, Smith *et al* 2016). Only very recently have a growing number of scenarios considered other NET options (Wise *et al* 2009, House *et al* 2011, Chen and Tavoni 2013, Fuss *et al* 2013, Humpenöder *et al* 2014, Strefler *et al* 2015, Kreidenweis *et al* 2016). It seems reasonable to assume that, if any, only portfolios of NETs could provide the amount of negative emissions suggested in the scenario literature at acceptable levels of risk (Fuss *et al* 2016, Smith *et al* 2016). The development of a literature that discusses NET portfolios therefore seems crucial and could become an important hub in the topic structure linking the different research themes.

Integrated scenarios have initiated and mainstreamed the discussion of negative emissions and their role in climate change mitigation (Herzog 2001, Riahi *et al* 2004, Fuss *et al* 2014, Riahi *et al* 2015), but they do not feature heavily in the topic structure nor in terms of publications included in the body of evidence identified here. In fact, a keyword search identifies just 33 papers referencing integrated assessment in our corpus that largely relate to the energy economics topic. There is a much wider integrated scenario literature available with mitigation pathways that involve negative emissions. However, negative emissions are not the primary focus of these studies and so issues of carbon dioxide removal are consequently not highlighted in title, keyword or abstract of these publications. It therefore seems appropriate not to include these studies into a core literature on NETs. However, any quantitative synthesis of the role of negative emissions in climate change mitigation will need to consider such work.

Topic modelling also proves to be a useful tool to discover prevailing discourses within a body of literature—much more so than simpler approaches such as title word clouds or community detection algorithms. For instance, the intrusion of SRM into our results and its close association with ocean fertilization and enhanced weathering shows how conspicuous these methods are in the eyes of authors who use the term 'geoengineering'. Of course, geoengineering has implicit connotations of global-scale anthropogenic (and potentially risky) interventions. But against this stands the enormous changes to terrestrial ecosystems that would be implied by the implementation of other land-based NETs. The emerging ethics literature on geoengineering might seek to expand on this issue further by exploring the different risk and governance challenges posed by different NETs. In addition, we observe a notable lack of policy and implementation discourse—most prominently around biochar - that should be urgently addressed. Hence, in view of the increasingly problematic task of aggregating scientific knowledge, topic modelling may provide a bird's eye summary of large literature corpora.

Scenario evidence suggests that meeting the climate goals of the Paris Agreement will require swift action that goes far beyond the promises countries made for reducing GHG emissions in the intended nationally determined contributions (INDCs). Unless global GHG emissions peak soon and substantial and sustained emission reductions follow, the dependence on NETs will continue to grow (IPCC 2014, Minx *et al* 2016). Therefore, understanding how to overcome political inertia internationally, regionally and nationally is of utmost importance. This is equally true for climate policies in general and those that target NETs development and deployment. In this sense, the modest engagement of social sciences and humanities in NETs research might be seen as a great worry by those who believe that more rapid progress on NETs is needed. If we do not fully comprehend the ethics and social dynamics around NETs, there might be little hope to succeed in deploying such technologies at required scales. The fast-growing calls to engage social sciences and humanities at the heart of climate change research might need to be strongly echoed for the issue of NETs (Corbera *et al* 2015, Victor 2015, Castree 2016, Minx *et al* 2016).

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