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Co-benefits of greenhouse gas mitigation: a review and classification by type, mitigation sector, and geography

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Abstract

The perceived inability of climate change mitigation goals alone to mobilize sufficient climate change mitigation efforts has, among other factors, led to growing research on the co-benefits of reducing greenhouse gas (GHG) emissions. This study conducts a systematic review (SR) of the literature on the co-benefits of mitigating GHG emissions resulting in 1554 papers. We analyze these papers using bibliometric analysis, including a keyword co-occurrence analysis. We then iteratively develop and present a typology of co-benefits, mitigation sectors, geographic scope, and methods based on the manual double coding of the papers resulting from the SR. We find that the co-benefits from GHG mitigation that have received the largest attention of researchers are impacts on ecosystems, economic activity, health, air pollution, and resource efficiency. The co-benefits that have received the least attention include the impacts on conflict and disaster resilience, poverty alleviation (or exacerbation), energy security, technological spillovers and innovation, and food security. Most research has investigated co-benefits from GHG mitigation in the agriculture, forestry and other land use (AFOLU), electricity, transport, and residential sectors, with the industrial sector being the subject of significantly less research. The largest number of co-benefits publications provide analysis at a global level, with relatively few studies providing local (city) level analysis or studying co-benefits in Oceanian or African contexts. Finally, science and engineering methods, in contrast to economic or social science methods, are the methods most commonly employed in co-benefits papers. We conclude that given the potential mobilizing power of understudied co-benefits (e.g. poverty alleviation) and local impacts, the magnitude of GHG emissions from the industrial sector, and the fact that Africa and South America are likely to be severely affected by climate change, there is an opportunity for the research community to fill these gaps.

1. Introduction

1.1. The policy context on co-benefits from GHG mitigation

The impact of anthropogenic greenhouse gas (GHG) emissions on the global climate is a major challenge for sustainable development (IPCC 2014). Since 1992 there has been a lot of activity in the international sphere to develop national plans to address the challenge of climate change, culminating in the 2015

Paris Agreement. To date, the parties to the Paris Agreement have submitted 165 pledges detailing their plans (among other things) to reduce emissions—these pledges are known as Intended Nationally Determined Contributions (INDCs) (UNFCCC 2017). However, even if these INDC pledges are met (and many may not be), they are widely acknowledged to be insufficient to limit the increase in global average temperature over pre-industrial levels by 2 °C (Robiou du Pont *et al* 2017).

Research has shown that there are many reasons why pledges to reduce GHG emissions and actions to date have been insufficient including politics, concerns about costs and fairness, and the fact that (in most places) the public does not rank climate change mitigation at the top of the list of important issues facing their country (Greenblatt and Wei 2016, Meinshausen *et al* 2015). This low prominence of concerns about climate change in the public sphere is largely explained by the fact that mitigation efforts (and costs) today are expected to largely result in avoided harms in the future and to ‘other people’ (Hansen *et al* 2013). People tend to prioritize economic growth and the improvement of their living standards—i.e. they want energy that is first ‘cheap’ and then clean—which means that protecting the benefits of people far away in the future is not high on the priority list (Ansolabehere and Konisky 2014).

The concern that climate change mitigation goals alone may not be able to catalyze sufficient public support to implement more aggressive GHG emissions mitigation efforts (Bollen *et al* 2009) has partly resulted in an increased interest in (and research on) other benefits from GHG mitigation, which will be referred to as ‘co-benefits’ from now on. These co-benefits include things like improvements in health outcomes and biodiversity.

In this work, we assess the state of knowledge on the co-benefits of GHG mitigation by developing and implementing a typology of co-benefits research that differentiates between the types of co-benefits, mitigation sectors, and geographic scales investigated, and the types of research methods used. We also summarize common metrics from a bibliometric and keyword co-occurrence analysis, including the journals that are publishing co-benefits research.

The rest of this paper is structured as follows. We first discuss the methods used in this review (section 2) and present the descriptive results from the systematic review and bibliometric analysis (section 3). We then describe the typology of co-benefits developed in this work (section 4), and present the results of applying it to the papers resulting from the systematic review (section 5). We conclude with a discussion of key insights from the analysis for researchers and policy makers (section 6).

Before delving into the main analysis of the article, however, we define co-benefits (section 1.2) and summarize why an assessment of the knowledge base in this space is timely and needed (section 1.3).

1.2. Defining co-benefits

Although a few studies discussed the health benefits of reducing GHG emissions in the late 1990s (Ekin 1996, Messner 1997, Wang and Smith 1999), the concept of co-benefits was not formally put forward until 2001 in the Intergovernmental Panel on Climate Change (IPCC) Third Assessment Report (IPCC 2001). Mayrhofer and Gupta (2016) summarized the evolution of the co-benefits concept and argued that this

term can be traced back to the concepts of ‘no-regrets’ policies and ‘double dividends’ for carbon taxation. According to the IPCC Third Assessment Report (IPCC 2001), ‘co-benefits are benefits of policies that are implemented for various reasons at the same time, including climate change mitigation, acknowledging that most policies designed to address GHG mitigation also have other, often at least equally important, rationales (e.g. related to objectives of development, sustainability, and equity)’.

The term ‘co-benefits’ is sometimes used to denote non-climate change mitigation benefits that are clearly mentioned as additional (if not primary) motives in the design and implementation of GHG mitigation policies. In this work, however, we also include in the term ‘co-benefits’ what the IPCC designates as ‘ancillary benefits’, which refer to side effects arising subsequently from the scheduled greenhouse gas mitigation policies (IPCC 2001). In other words, we also include in our definition of co-benefits (and thus in this review) the impacts of particular climate change mitigation efforts that may not have yet been used as primary or secondary policy goals.

Finally, following the IPCC Fifth Assessment Report (IPCC 2014), our definition of co-benefits from GHG mitigation includes both positive effects and negative effects (also known as ‘adverse side effects’). Even though the value of research on co-benefits to motivate additional climate change mitigation efforts from policy makers or to increase public support for climate change mitigation efforts stems from the ‘positive’ co-benefits, it is clearly important to understand the adverse effects of such mitigation efforts, as they will also affect policy making and should shape future research. Thus, for completeness, we include adverse side-effects in the definition of ‘co-benefits’ used in this systematic review. To summarize, in this work we define ‘co-benefits’ to include ‘positive’ co-benefits, ancillary benefits and adverse side effects.

1.3. The need to better understand the body of knowledge about co-benefits

Many researchers working on climate change mitigation and public health will not need a systematic review and additional analysis to conclude that a lot of research has investigated GHG mitigation co-benefits in the form of reduced air pollution and improved health outcomes (e.g. Buonocore *et al* 2016, Driscoll *et al* 2015, Tang *et al* 2014, West *et al* 2013). In addition, it is relatively well-known that there is a body of research on the protection of biodiversity, the preservation of watersheds and soil, and the reclamation of land that can result from GHG mitigation activities focusing on reducing deforestation. The link between understanding these types of co-benefits from GHG mitigation and making the case for action has also been made. For instance, Dudek *et al* (2003) have argued that local authorities in Russia have been encouraged to provide more finance for forest projects by emphasizing

benefits in terms of both AFOLU emissions reductions and other ecosystem benefits from preventing deforestation.

Having said that, researchers and policy makers would benefit from a systematic and comprehensive analysis of the types of co-benefits that have been identified and investigated, in which GHG mitigation sectors such co-benefits may accrue, and the geographic focus of research on co-benefits. Similarly, researchers and students would also benefit from a detailed and systematic understanding of what types of methods and data have been used to determine the existence (and in some cases magnitude) of different types of co-benefits. The reason for this is that, as we know from work on policy analysis, translating policies or insights from one place to another is extremely hard unless all underlying mechanisms are perfectly understood (Cartwright and Hardie 2012), something that is particularly difficult in complex systems (Anadon *et al* 2016). Thus, having information about the types of co-benefits from GHG mitigation in a particular sector and location would help support policy decisions in that particular location (and, in some cases, elsewhere, provided there is appropriate local knowledge) by providing information about the benefits (and sometimes costs) of GHG mitigation. Similarly, a lack of research in a particular space might signal a missed opportunity for researchers and policy makers to identify possible additional co-benefits (which again, includes benefits and costs) from GHG mitigation.

Knowledge on the co-benefits of mitigating GHG emissions in different locations and sectors can serve as an input to cost-benefit analysis or to assessments of tradeoffs of climate change mitigation policies. But perhaps more importantly than improving cost-benefit analysis, knowledge about the co-benefits of GHG mitigation (particularly at the local level) may provide information and rationales for taking action to mitigate GHG emissions that are more persuasive to particular sets of decision makers or the public as a whole.

The complexity of understanding what we know about the co-benefits of GHG mitigation is significant given the heterogeneity of the co-benefits (e.g. from health benefits, to increased resilience, to increased economic development outcomes), the mitigation sectors in which these co-benefits may be realized (e.g. agriculture, industry, electricity and transportation sectors), and the fact that such co-benefits may be highly dependent on where the GHG mitigation takes place (e.g. in New York City, in the Indus basin, in China, or globally). Given that countries and regions vary significantly in their susceptibility to climate change, their previous and future contributions to worldwide GHG emissions, and their capacity to share the responsibility of mitigating GHG emissions (Cazorla and Toman 2000), having robust evidence regarding what co-benefits may accrue from a particular GHG mitigation effort in a particular sector and location may help spur action. In addition, a comprehensive understanding of the

co-benefits of climate change mitigation policies can also help inform country negotiators in international environmental negotiations (Pittel and Rübbecke 2007).

There have been previous reviews in the area of co-benefits, but their scope differs significantly from this review. In particular, most of the existing reviews were conducted from the perspective of either: (a) particular co-benefits (e.g. health co-benefits (Remais *et al* 2014, Cheng and Berry 2013, Bell *et al* 2008)); (b) the co-benefits of climate change adaptation efforts (VijayaVenkataRaman *et al* 2012) as opposed to GHG mitigation efforts; (c) the co-benefits of mitigation in a subset of sectors (e.g. transport sector (Kwan and Hashim 2016), AFOLU sector (Bustamante *et al* 2014, Verspecht *et al* 2012), energy sector (Smith and Haigler 2008)); (d) the co-benefits in a small number of geographical locations (e.g. South Africa (Klausbruckner *et al* 2016), Bangladesh (Ahammad *et al* 2014)); or (e) methodologies for quantifying and valuing the co-benefits of GHG mitigation (Ürge-Vorsatz *et al* 2014).

In contrast, this study reviews the overall literature on GHG mitigation co-benefits between 2001 (the year when the term was coined) and 2016 both qualitatively and quantitatively to develop a systematic and comprehensive typology of co-benefits across a range of dimensions, assess the relative effort of researchers on different efforts, and identify possible gaps in the body of knowledge. We use a systematic review and bibliometrics (the detailed analysis of publication trends in scientific journals) to characterize the information such as document type, journals, authors, and article citations. The bibliometric analysis includes a keyword co-occurrence analysis, network analysis, and citation analysis. We then analyze the full text of the papers resulting from the systematic review. This analysis involves the hand-coding of the papers by two researchers independently to classify papers according to the types of co-benefits, mitigation sectors and geographic levels investigated, as well as according to the research methods used. Our comprehensive approach allows us to systematically document the areas of focus of the research community across a wide range of co-benefits, sectors, geographies, and methods.

2. Methods

2.1. Overview of methods

This study relies on a systematic review, bibliometric analysis, and network analysis. We then hand-code the papers resulting from the systematic review and develop and implement a typology of co-benefits research. We now provide more background on the methods used in this paper before providing detail on our particular implementation in sections 3–5.

Systematic reviews follow rigorous transparent processes to extract findings from a body of research in a replicable manner, in some cases to inform future

research and policy (Stoker and Evans 2016). Systematic reviews involve the systematic identification, mapping, and synthesis of the body of research. The systematic review was conducted iteratively with different rounds of full-text analysis.

Bibliometric analysis are routinely used to provide a quantitative analysis of academic literature and to evaluate the performance of a specific study area (Nicolaisen 2010, Wei *et al* 2015). It is often employed to assess characteristics of the literature in terms of journals, authors, institutes, countries, citations, international collaborations and so on (Li and Zhao 2015). Bibliometric analysis has been widely used to study the state of knowledge in the area of energy and environmental policy. Examples of bibliometric analysis in this space include the study of carbon markets (Du *et al* 2015), carbon taxes (Zhang *et al* 2016), climate policy modeling (Wei *et al* 2015), low-carbon energy technology investment (Yu *et al* 2016), climate change research (Haunschild *et al* 2016) and energy management strategies for hybrid electric vehicles (Zhang *et al* 2015).

We start with a systematic review. We then conduct a traditional bibliometric analysis of the corpus of papers extracted during the systematic review. We present the results from the bibliometric analysis detailing main research subjects, lead authors and highly cited publications, etc. We then use network analysis to visualize some of these results. Finally, we conduct a detailed analysis of the papers resulting from the systematic review that entails the a hand-coded mapping analysis developed iteratively categorizing papers (using the abstract or the full text) into different co-benefits, sectors, areas of geographic focus, and methods. Such additional and more targeted classification of the papers of co-benefits aims to better inform researchers in the field and policy makers is not possible using solely traditional automated bibliometric analysis.

2.2. Details of method implementation

2.2.1. Identification of the corpus of papers in the systematic review

The raw list of publications analyzed in this paper was obtained from Web of Science, which includes Science Citation Index Expanded (SCI-E) and Social Sciences Citation Index (SSCI) on 19 February 2017 to ensure that virtually all papers from the year 2016 were covered (we did not impose a limit in terms of starting year). The first step of the systematic review was to iteratively develop a search string to ensure that all relevant papers were captured. The iterative process involved analyzing the literature to identify synonymous terms and revising the search string until the results stopped changing. The final search string, which led to the identification of 4766 papers, is included in the appendices (table A1).

The second step involved excluding the publications that included correct terms but were on unrelated topics. Visual inspection of the abstract of the papers (and the full text when necessary to make a

determination), for example, revealed that a significant number of publications involved unrelated papers from the chemical or medical sciences instead of the climate change mitigation co-benefits. By including an 'exclusion criteria' with words that were common in unrelated papers, such as catalyst, reaction, chemical, metabolism and chemotherapy, the list of papers to be considered in the next step of analysis was reduced to 2277 papers.

The third step involved the one-by-one examination of these papers by two researchers working independently to further exclude other unrelated papers. The reconciliation of the exclusions between the two independent researchers led to a final list of 1554 papers on co-benefits from GHG mitigation for further in-depth analysis.

For completeness, we have included the full search string (including the words used to exclude unrelated papers) in the appendices (table A2). We found that the number of publications on co-benefits before 2001 was very small (less than 1% of the total). The reason for this is that, as previously explained, the concept of co-benefits was formally put forward in 2001. Because of this, we define the time window for our analysis as 1 January 2001–31 December 2016.

Using the categories available in the dataset from Web of Science, we analyzed the 1554 publications in the final dataset according to their language, document type, subject categories, journals, publication outputs and citations, authors, institutes and countries. These results are covered in section 3.

2.2.2. Network analysis

A second stage of the analysis involved a network analysis by using the software BibExcel and Pajek. BibExcel was used to extract information which was downloaded from the dataset of Web of Science. Pajek was then employed for visualization of the analyzed results. The cooperation across authors, institutes and countries, the network of highly cited publications and frequently occurred keywords were analyzed accordingly in section 3.

2.2.3. Development and implementation of the classification of co-benefits research

The third and final stage of the research involved the mapping of the papers identified in the systematic review. This involved hand-coding the papers from the systematic review into different types of co-benefits in different sectors and geographic locations, resulting in the typology of co-benefits presented in section 4. We also classify the papers according to the main method used.

We categorized the co-benefits into ten types: ecosystem impacts, economic impacts, health impacts, air pollution impacts, resource efficiency impacts, conflict and disaster resilience impacts, distributional impacts, energy security impacts, technological spillover and innovation impacts, and food security

impacts. The categorization of sectors for GHG mitigation resulted in eight types: AFOLU sector, electricity sector, transport sector, residential sector, governmental sector, industrial sector, marine sector, and buildings sector. Four geographic levels were used to map papers: international level, national level, regional level (a connected part of areas within a country), and city level. Finally, the corpus of papers from the review were classified according to the continent or continents that were being covered: Europe, Asia, North America, Oceania, Africa and South America. We also classified papers depending on what was the main method used: science and engineering methods, economic methods and social science methods. The papers resulting from the systematic review coded according to these five dimensions. The results from this coding analysis are available in the supplementary data available at stacks.iop.org/ERL/12/123001/mmedia. Papers that covered more than one co-benefit, more than one sector, country, or method appear more than once in the supplementary data. To visualize the results from the mapping and coding exercise across the co-benefit type, mitigation sector, geographic level, continent, and research method, we use Sankey diagrams implemented through the Tableau software, as shown in section 5.

3. Results from the bibliometric analysis of co-benefit papers

In this section we describe the field of co-benefits publications explaining in turn: the general statistics on the evolution of co-benefits publications (section 3.1), the most prolific authors, institutes and countries (section 3.2), the network of cooperation across authors and their affiliations in this space (section 3.3), a citation analysis (section 3.4), an analysis of the most commonly co-occurring keywords (section 3.5), and an analysis of the research methods used in co-benefits publications using keywords (section 3.6).

3.1. General statistics on co-benefit publications

The 1554 publications retrieved in this study include publications in English, German, French, Polish and Italian, with English, as expected, accounting for the vast majority (99.4%) of the publications. Articles (as opposed to letters, reviews, or book chapters, for instance) account for the majority (88.0%) of the total number of publications. The appendices (table A3) include more descriptive information on languages and publication types.

As one may expect, given the fact that the term ‘co-benefits’ was created in 2001, reviews on the topic came out relatively recently; more than 50% of the reviews were conducted between 2013 and 2016, with the first review being released in 2002. According to Web of Science Categories (including environmental sciences, environmental studies, energy fuels, ecology, green

sustainable science technology, economics, meteorology atmospheric sciences, engineering environmental, public environmental occupational health, geography, forestry, etc), the top five subjects which account for 61.2% of the total subjects used to categorize the papers in Web of Science are environmental sciences⁶ (21.8%), environmental studies⁷ (15.5%), energy fuels (9.2%), ecology (5.1%) and green sustainable science technology (9.6%). *Energy Policy* is the journal in which the largest number of co-benefits papers was published, with 108 publications (7.0% of the total). The top ten journals with the largest number of publications on co-benefits from GHG mitigation are listed in the appendices (table A4).

Figure 1 shows the evolution of publications on co-benefits from GHG emissions mitigation over the period studied. The increase in the number of publications in this space has been exponential, starting from nine publications in 2001 (when the term ‘co-benefits’ was coined) to 344 publications in 2016 with slight fluctuations.

3.2. Most prevalent authors, institutes and countries

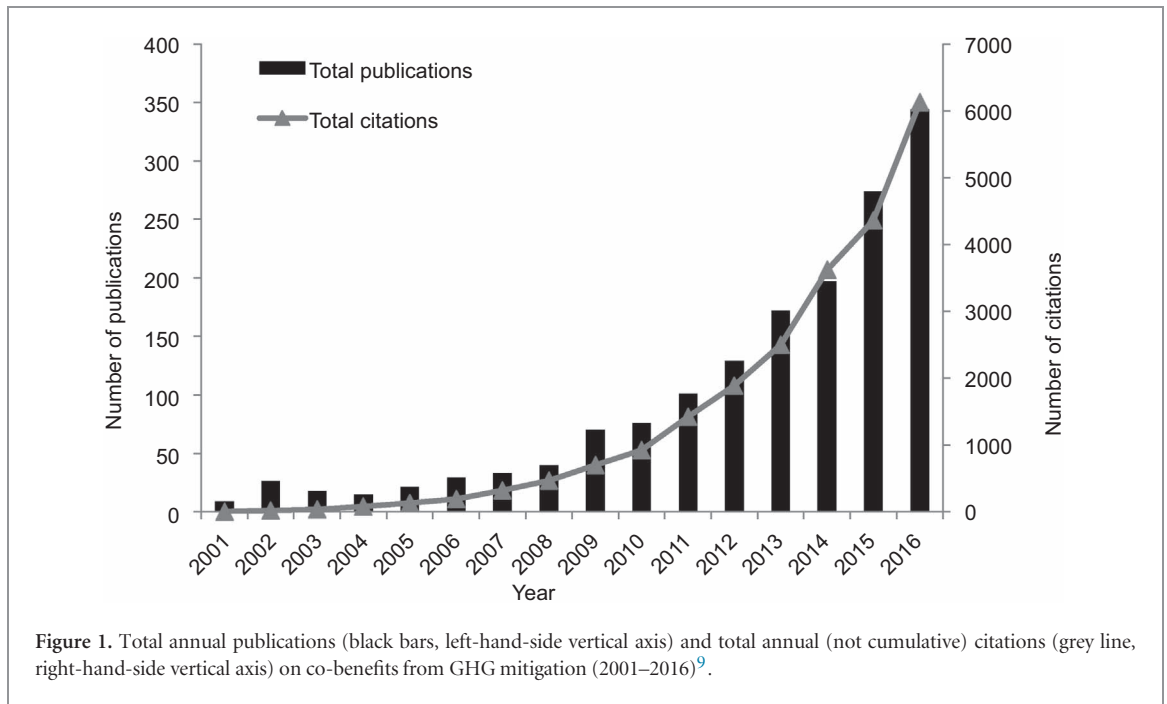
The bibliometric analysis of productive authors, institutes and countries can provide researchers and policy makers with useful information to facilitate their understanding of this study area. The top 12 most prolific authors (with more than seven publications⁸) are presented in the appendix (table A5). Three of these most prolific authors are based at IIASA in Austria, two are based in the United Kingdom and two in Australia. The publications of these 12 authors account for 7.7% of the total number of co-benefit publications.

Table A6 in the appendix shows the 11 most productive research institutes, defined as those that are authors or co-authors in more than 20 publications on co-benefits. IIASA was present as an institute in the largest number of publications (49, or 3.2% of the total). Nine of these research institutes are universities, one is a governmental organization and one is non-governmental organization. Four of these institutes are located in the UK and two in the Netherlands. The output of these 11 institutions makes up 21.0% of the total number of publications in this space. In spite of the lack of US-based authors and institutions in the ‘top’ spots, with the exception of the University of California Berkeley, overall, publications written

⁶ Environmental sciences is a stand-alone subject that draws on fundamental scientific knowledge in mathematics, chemistry, physics, and biology coupled with specialization in a particular area of science to provide advanced scientific and quantitative understanding of contemporary environmental challenges.

⁷ Environmental Studies is a subject that provides a broadly integrated understanding to the social, political, and historical facets of our environmental challenges with focus on policy, law, and sociality aspect of these challenges.

⁸ The number of publications chosen here and similar numbers chosen in the following text are for better and clearer illustration of related information.



by US-based scientists led the total output of co-benefit publications over time (they are just less concentrated). This can be seen in the annual academic performance of the top six most productive countries as illustrated in figure 2. The country with the largest number of publications was the United States, followed by the United Kingdom.

3.3. Network analysis of cooperation across authors, institutes and countries

A network analysis of scientific collaborators provides insights about possible complementarities among researchers as well as of potential gaps.

The red dots in figure 3 show the top 21 institutions in terms of the number of papers on co-benefits with at least one author from that institution. The existence of the black lines connecting the institutions indicate co-benefits papers with at least one author from each of the connected institutions; the wider the black line, the larger number of joint papers between those institutions.

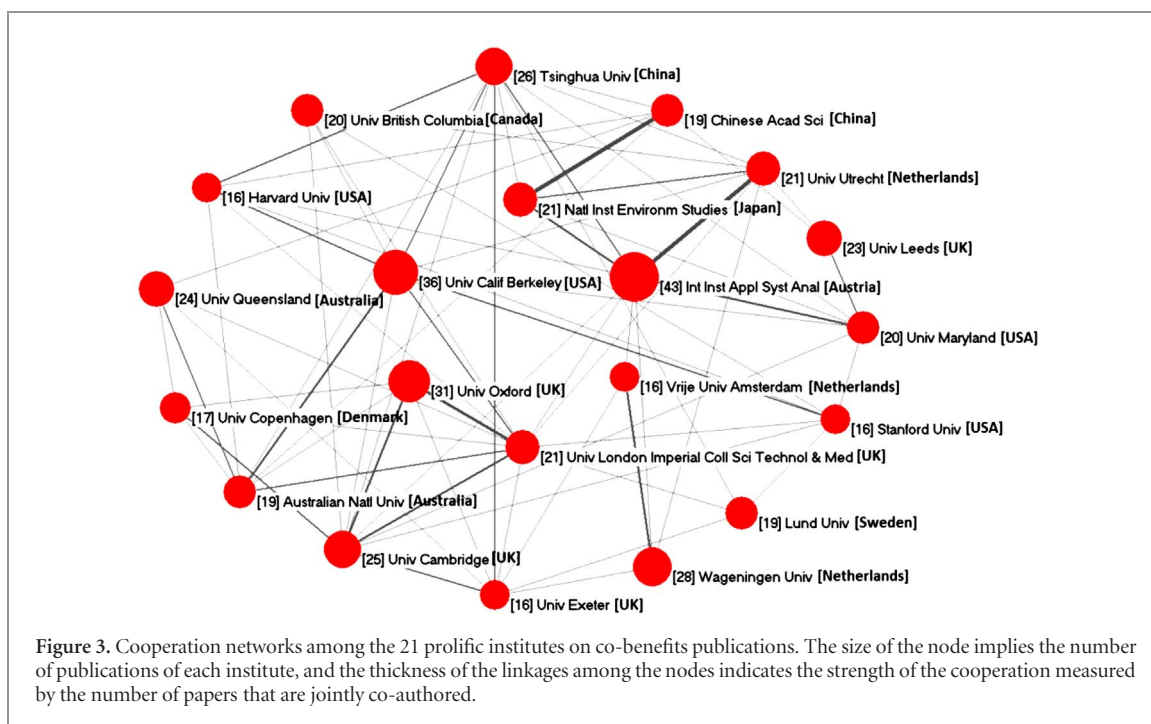
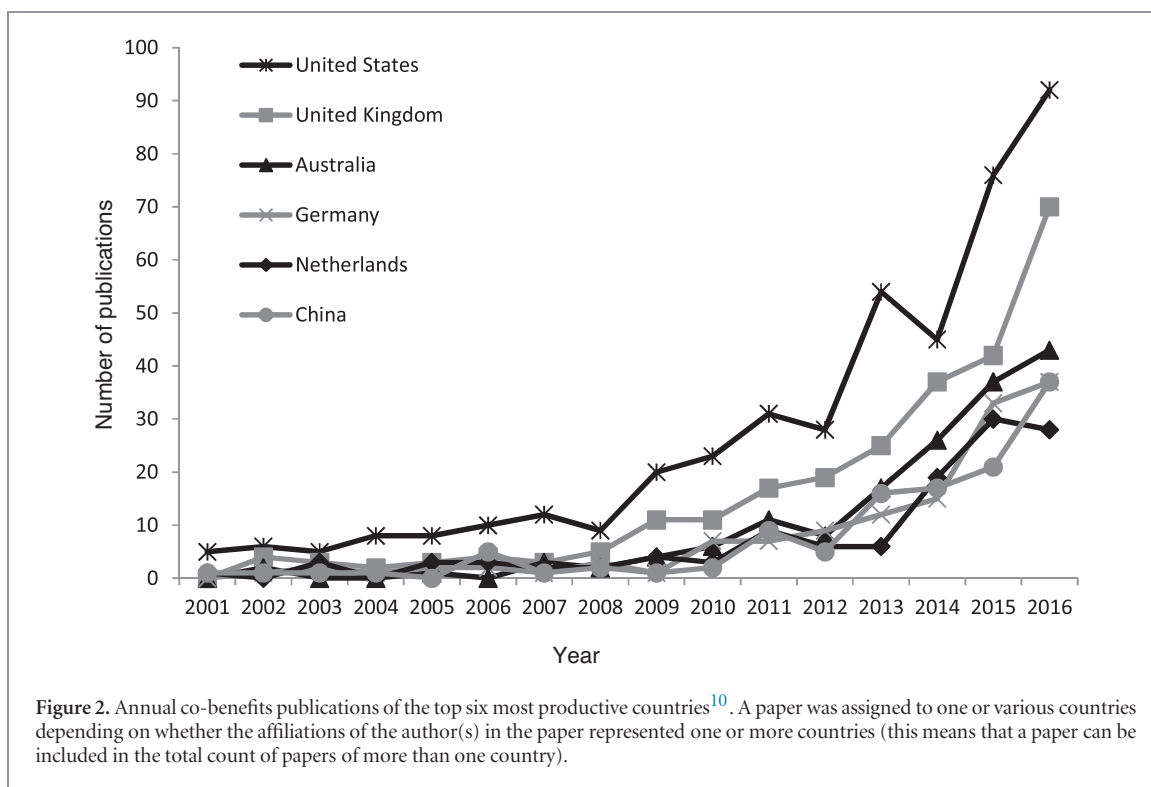
Imperial College in London cooperated the most frequently with other 13 institutes and it was followed by Tsinghua University in Beijing, which cooperated with 11 institutes. The University of Cambridge and IIASA were in the third-most-collaborative groups by having ten and nine joint publications respectively. Figure 3 shows that geographic proximity is somewhat correlated to publication cooperation in co-benefits, with small clusters of more intense collaboration in

the UK (Cambridge, Imperial College and Oxford), continental Europe (as denoted by IIASA and the University of Utrecht), and East Asia (as denoted by the National Institute of Environmental Studies in Japan and the Chinese Academy of Sciences). Such intensity of regional collaboration can be partly explained, as we will show in section 5.2 by the prevalence of national and international analysis on co-benefits, as opposed to urban or city level analysis. In the appendix (figure A1) we include a network analysis of the most collaborative authors. The most collaborative countries are also presented in the appendices (figure A2).

3.4. Citation analysis

Citation analysis is the evaluation of the frequency, patterns, and graphs of citations in articles and books (Buzydlowski *et al* 2002, Rubin 1998). Citations in articles play an important role to understand the importance of particular pieces of research as measured by connections to other research works (Garfield and Merton 1979). We conducted two types of citation analysis. First, we conducted a backward citation analysis of the 1554 co-benefits publications that constitute our corpus of co-benefits publications (as described in section 2). This backward citation analysis involves analyzing what articles were cited most frequently by the co-benefits articles, such most highly cited articles may or may not be directly related to the co-benefits of reducing GHGs. Figure A3 in the appendix depicts the results of the backward citation analysis. It shows the 18 studies that were cited more than 25 times by the papers in our dataset. Overall, analysis indicates that co-benefits research has mostly drawn upon research in epidemiology (articles in *The Lancet*) and ecology. This finding is explained by our analysis in section 3.5

⁹ The evolution of the number of citations, exhibits a growing tendency and can be divided into two periods. During the first period 2001–2010, the total number of citations increased more slowly, from 3–856 times at an annual average rate of increase of 81.5%. The period between 2010 and 2016 exhibits an annual average rate of increase at 31.5%, reaching 5834 citations for these papers in 2016.

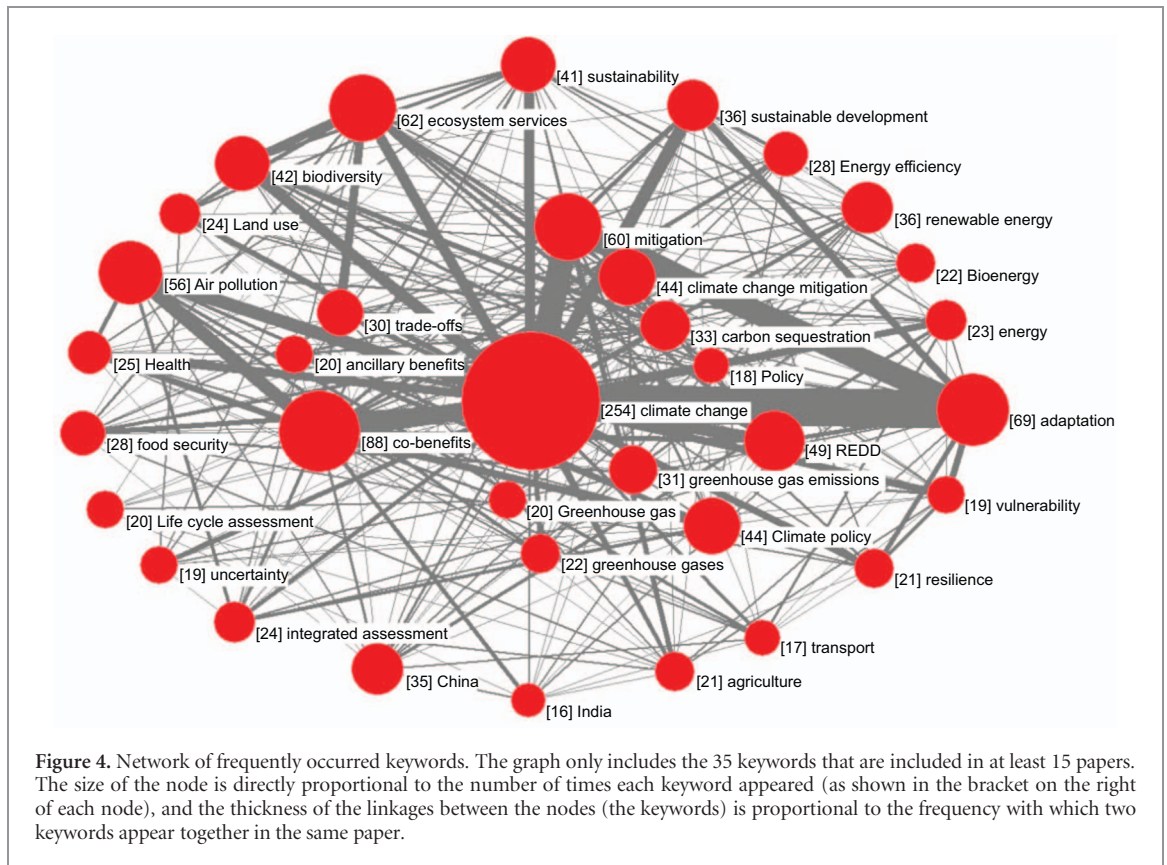


indicating that health and biodiversity co-benefits of GHG have been the most widely investigated topics.

Second, we conduct a forward citation analysis, namely, an analysis of the publications that cited the 1554 publications in our database. Forward citation analyses give an indication of the relative importance of different papers (Garfield 1979), although they

are imperfect measures of scientific merit since, for instance, citations are also a function of the research effort in a particular area (the number of researchers in a field) and field-specific norms (Adler *et al* 2008). In addition, papers that have been out for a longer period of time have more of a chance of being cited, i.e. a 2016 paper with five citations in 2016 may end up with the same citations in 4 years as a paper published in 2012 with 100 citations in 2016. The top ten papers in our database with the largest number of forward citations are shown in the appendices (table A7).

¹⁰ It should be noted that in this study China just refers to mainland China and documents from Taiwan, Hong Kong, Macao are not included in China.



3.5. Keyword co-occurrence analysis

Co-occurrence analysis of keywords is used to indicate the substantive content of documents by statistically investigating the keywords (terms) that appear together in the same document (Buzydlowski *et al* 2002). The 1554 articles in this study contain 4045 individual keywords, which are terms (typically somewhere between three and five) provided by the authors upon submission of their scientific publication. Figure 4 shows the 35 keywords that appear more than 15 times in this database, indicating that only a small portion of keywords are frequently used. The fact that only a few keywords are used more frequently is partly explained, again by the wide range of co-benefits, sectors, geographies and methods covered in co-benefits research, as we uncover in section 4.

The analysis of the frequency and co-occurrence of keywords provides some insight into the areas of focus in terms of co-benefits, sectors and countries, as well as methodologies. We discuss these findings in turn.

In terms of focus areas, figure 4 shows groups of words that are co-occurring, in particular: air pollution, co-benefits, and climate change; ecosystem services, biodiversity, climate change and adaptation; and mitigation, adaptation and climate change. The first two groups, in particular, indicate that air pollution and ecosystem services are the areas of research on co-benefits that have seen the largest amount of effort. As hinted in the introduction, there are many other co-benefits. GHG mitigation from transport sector and agriculture sector are more frequently appeared in the keywords. We can also see a significant focus

on national level analysis, in particular of co-benefits in China and India. Finally, figure 4 also provides a sense of the most commonly used methodologies in the work on co-benefits, in particular integrated assessment models and life cycle assessment.

However, we found this keyword occurrence and co-occurrence analysis insufficient to understand research on co-benefits and identify gaps. As we discuss in section 2, we found no study categorizing co-benefit research in terms of co-benefit types, sectors for GHG mitigation, and geographic scope. Because of this, we iteratively developed and applied such a classification (typology) using the full content of the papers, as opposed to just keywords and keyword occurrence, using our database. Section 4 details the typology we developed in the course of conducting full text analysis of the 1554 papers in the systematic review.

3.6. Keyword analysis of methods used in co-benefit papers

The analysis of keywords indicated that the most frequently used methods are integrated assessment models and life cycle assessments. More than 5.0% of the papers explicitly mentioned these two methods in the keywords. In the appendix (table A8) we provide specific examples of some of the most commonly used methods.

The methods that are less frequently mentioned in the keywords also include risk assessment, optimization, cost-benefit analysis, Input-Output analysis, computable general equilibrium (CGE) model, GAINS model, partial equilibrium model, multi-criteria assessment, Environmental Benefits Mapping and Analysis

Table 1. Typology of co-benefits papers. Developed inductively and iteratively through the hand-coding of papers from the systematic review according to co-benefit type, mitigation sector, geographic scope, continent, and research method.

Co-benefit type	Mitigation sector	Geographic scope	Continent	Method
<ul style="list-style-type: none"> • Ecosystem impacts (309) • Economic impacts (285) • Health impacts (220) • Resource efficiency impacts (171) • Air pollution impacts (177) • Conflict and disaster resilience impacts (149) • Distributional impacts (102) • Energy security impacts (70) • Technological spillover and innovation impacts (66) • Food security impacts (55) • Other (28) 	<ul style="list-style-type: none"> • AFOLU (513) • Electricity (400) • Transport (165) • Residential (152) • Governmental (109) • Industry (83) • Marine (35) • Buildings (22) • Other (43) 	<ul style="list-style-type: none"> • International (608) • National (574) • Regional (297) • City (143) 	<ul style="list-style-type: none"> • Global (495) • Europe (339) • Asia (300) • North America (174) • South America (127) • Oceania (98) • Africa (89) 	<ul style="list-style-type: none"> • Science and engineering (524) • Economic (253) • Social science (739) • Other (106)

Program (BenMAP), linear programming, and other modeling methods. We include a more detailed description of the analysis of methods based on keywords in the appendix (table A8). Section 5.4 describes the results from the typology we developed to classify the co-benefits papers from the systematic review considering the full paper, and not just the keywords used by the authors when submitting their paper. This classification by method going beyond keywords allows us to characterize the full set of papers from the systematic review.

4. Typology of co-benefits publications

We create a four-dimensional typology of co-benefits publications covering co-benefit type, mitigation sector, geographic level, and geographic focus by analyzing the abstract of each paper and (when needed to make a determination) the full-text of the co-benefits papers resulting from the systematic review. We also classify papers according to the method used, adding a fifth dimension.

Unlike the summary of the hotspots based on frequently occurring keywords in section 3.5, the iterative hand-coded classification by two independent researchers presented here resulted in ten types of co-benefits, eight climate change mitigation sectors, four types of geographic levels, six continents and three high-level types of methods, as presented in table 1 and explained in sections 4.1–4.3.

The number of papers for each category is also shown in table 1 in brackets to give a first impression of the relative research activity in the different categories. We measure activity in each category of the typology by counting the number of papers instead of weighting them by citations or journal impact factor. We do not present results weighted by patent citations because this is a relatively new research area with a lot of recent papers. Comparing recent papers from, for instance, 2014–2016 to older papers on the basis of citations would not reflect the fact that many of the papers (which are recent), which are recent, will not have

had a chance to be cited as much. Having said this, for the work in section 3.4 we conducted a forward citation analysis and we found that the results we present in terms of the prevalence of research on different co-benefits, sectors, geographies, continents, methods, etc. in figures 6–9 in section 5 would not change significantly if we presented results weighted by citations.

We do not present results weighted by journal impact factor because of the multi-disciplinary nature of the research. Impact factors in the social and natural sciences, for example, tend to be very different and this could skew results. Such weighing by impact factor could suggest that there is a lot more work in one particular co-benefit just because the field of research that has devoted more research in that space has journals with higher impact factors. Thus, we have not included an analysis of the prevalence of research in different areas weighted by impact factors in the main text. However, in the supplementary materials we include information about the impact factors of each journal in the database to complement our analysis.

4.1. Co-benefit types

The iterative development of the typology presented in table 1 resulted from the abstract and then full-text analysis of the 1554 papers from the systematic review. In what follows, we describe each of the 10 types of co-benefit types identified and provide one or several example papers in each category.

Some of the co-benefit types can be described as ‘direct’ co-benefits, while others are ‘indirect’ co-benefits. Direct co-benefits from climate change mitigation policies include ecosystem impacts, air pollutants, health impact, resource efficiency, energy security and technological innovation. Some co-benefits can be both direct and indirect. For example, food security can be a direct impact of mitigation policy if it leads to more domestic production and an indirect impact if reduced GHG emissions lead to less drought and an increase in crop-yields. Increased economic activity, conflict impact and disaster resilience,

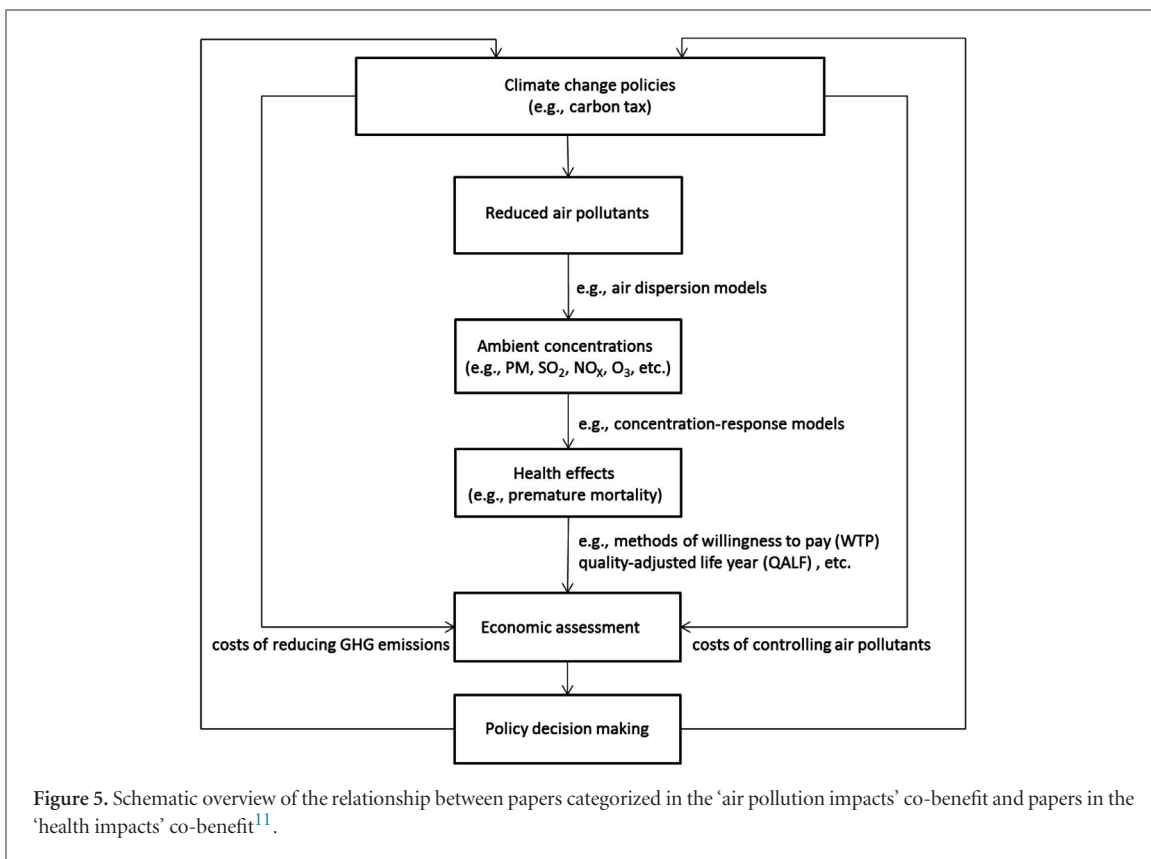


Figure 5. Schematic overview of the relationship between papers categorized in the 'air pollution impacts' co-benefit and papers in the 'health impacts' co-benefit¹¹.

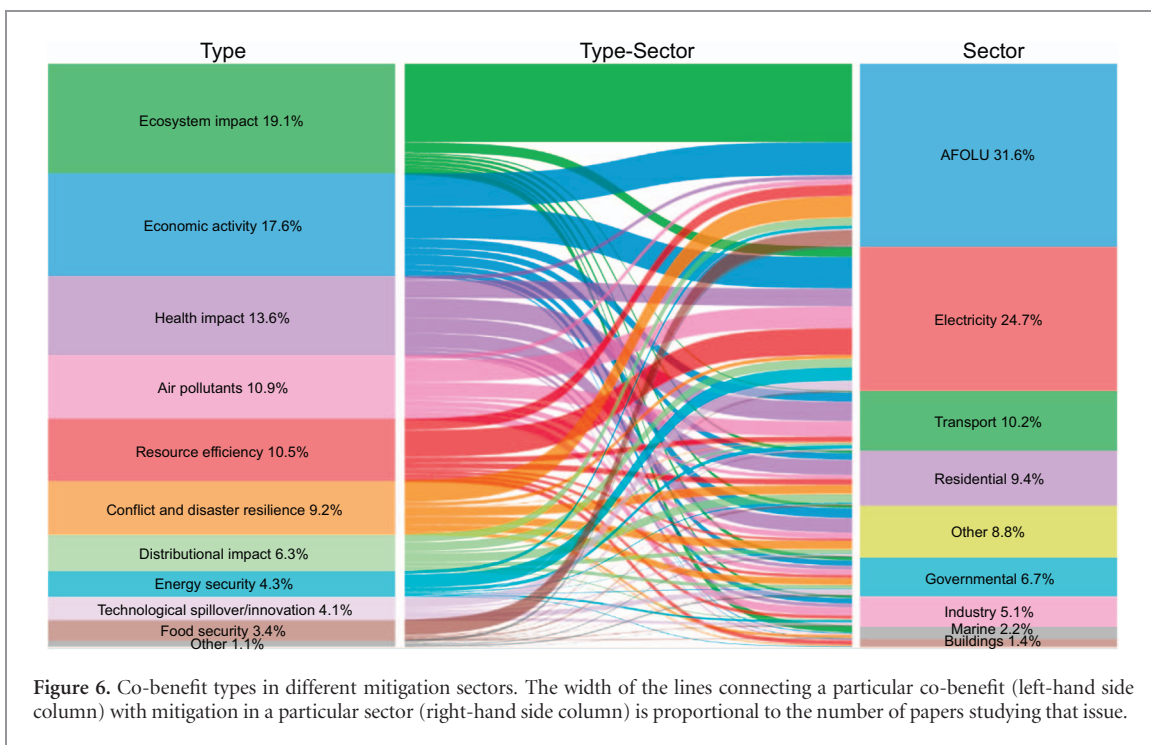


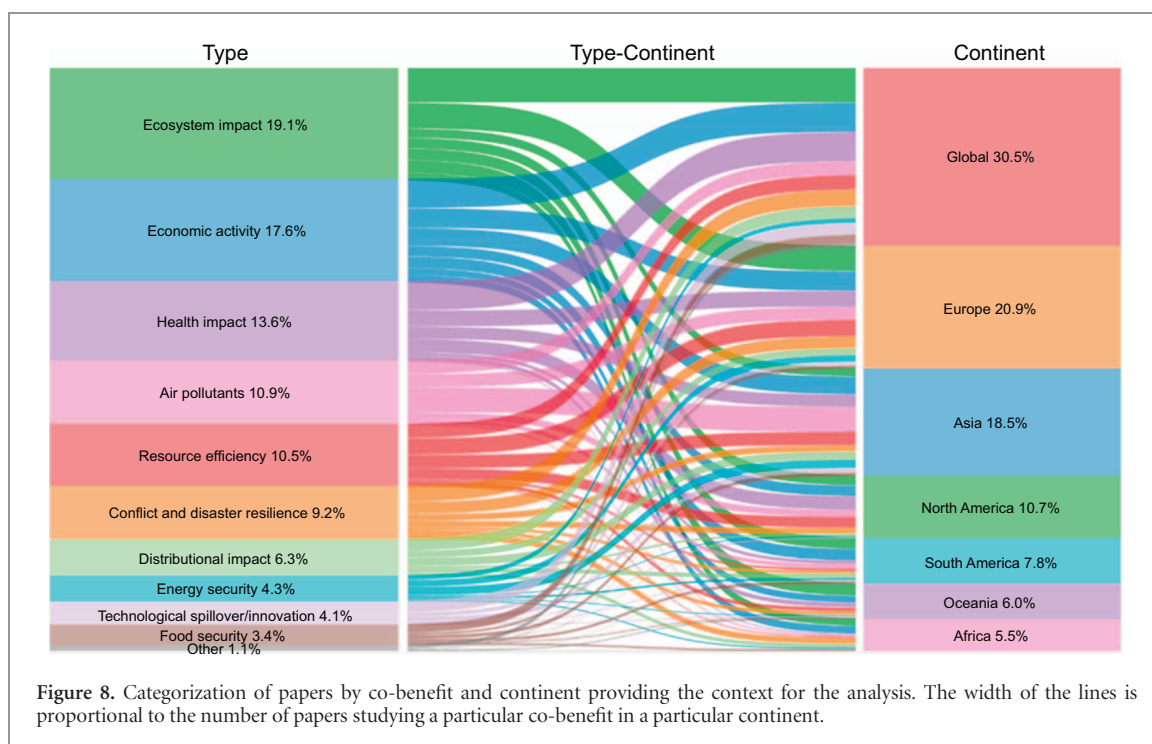
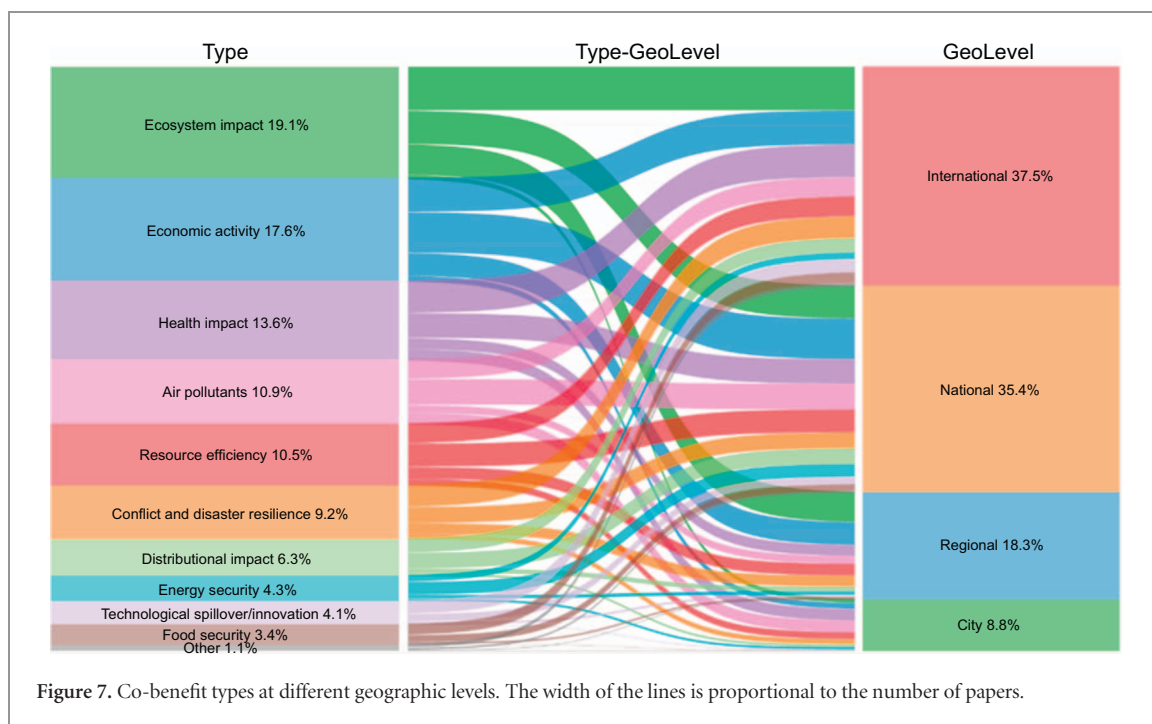
Figure 6. Co-benefit types in different mitigation sectors. The width of the lines connecting a particular co-benefit (left-hand side column) with mitigation in a particular sector (right-hand side column) is proportional to the number of papers studying that issue.

and distributional impacts can also be direct or indirect co-benefits.

¹¹ This figure was created by the authors using components of figures and text presented in related research, most importantly Bell *et al* (2008), Cao (2007), Cifuentes *et al* (2000), and Dessus and O'Connor (2003).

4.1.1. Ecosystem impacts

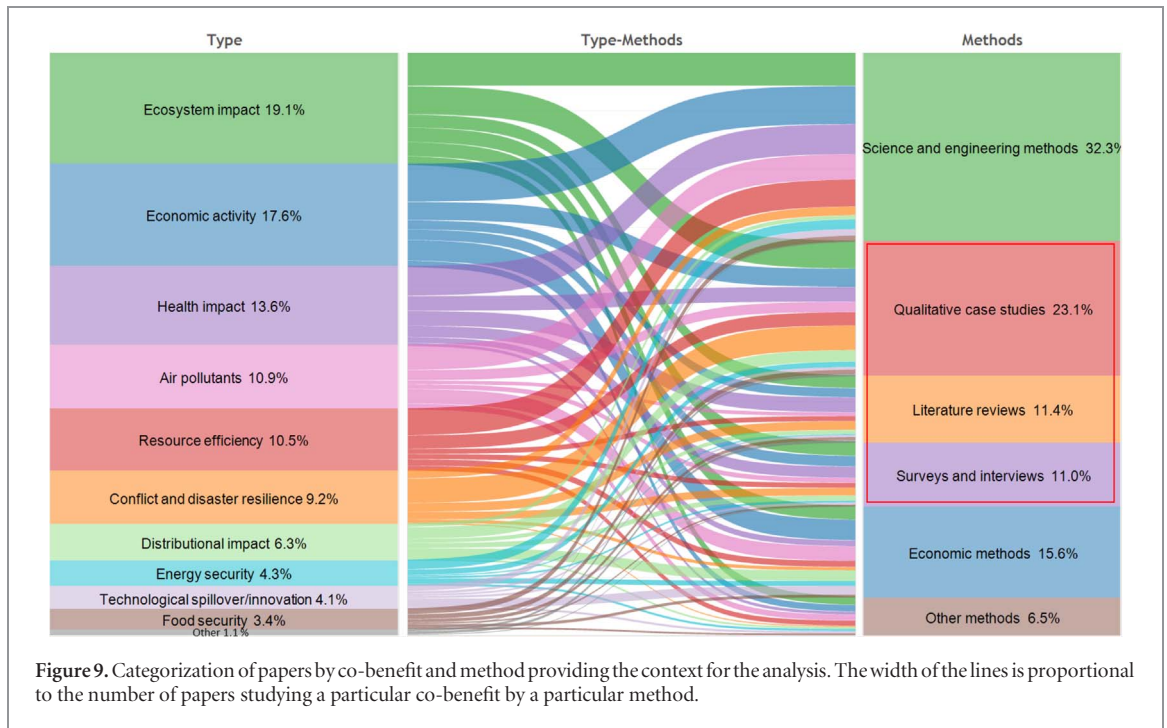
An important co-benefit of mitigating GHGs identified in the literature is the prevention of negative impacts on ecosystems, including biodiversity loss, ocean acidification, soil degradation, water pollution, and the loss of other ecosystem services.



The work of Phelps *et al* (2012), for example, falls in the category of ecosystem impacts co-benefit. Their work estimates the probability of critical biodiversity losses with events caused by climate change using five methods to link forest-based climate change mitigation with biodiversity conservation.

Many of the publications on the Reducing Emissions from Deforestation and Forest Degradation (REDD+) program developed by the United Nations Framework Convention on Climate Change also fall into this category of benefits. The publications reviewed indicate that the REDD+ program has ecosystem

co-benefits that include reductions in biodiversity losses and soil erosion through an increase in forest-based carbon sequestration (Harris *et al* 2008), as well as other co-benefits in the space of resource efficiency impact (which we will discuss in section 4.1.5 below), including conserving water and other natural resources (Chhatre *et al* 2012). Climate policies can also have co-benefits of mitigating ocean acidification on account of their common driver: CO₂. Therefore, climate change mitigation policies can alleviate the change of a significantly productive marine ecosystem structure (Kirby *et al* 2009). Furthermore, marine life and humans will



not be widely impacted by the phenomenon of ocean acidification (Harrould-Kolieb and Herr 2012).

4.1.2. Economic impacts

The co-benefit of economic impacts includes economic development, employment, and productivity increases (e.g. improvements in crop yields).

For example, Jochem and Madlener (2003) estimated that the macroeconomic effects from climate mitigation can be slightly negative to positive, depending on model structure as well as on assumptions on capital and labor markets. Fisher *et al* (2011) showed that climate change mitigation through REDD+ mechanism in Tanzania was associated with increases in agricultural yields.

4.1.3. Air pollution impacts

Significant work has been devoted to estimating the impact of policies to reduce GHG emissions, such as carbon taxes, emissions trading systems market and energy efficiency improvements, on the co-benefit of reducing air pollution (Rypdal *et al* 2007, Zhang *et al* 2015, Nemet *et al* 2010).

A large number of studies have been focused on air pollutants, which include particulate matter (PM₁₀, PM_{2.5}), SO₂, NO_x, ozone and black carbon. For example, Bollen (2015) used a CGE model to analyze the air pollution co-benefits from climate policies in Europe and indicated that the substantial regional impacts in terms of reduced air pollution can provide an additional motivation for reducing GHGs. Dong *et al* (2015) conducted an analysis at a more granular level. They measured the air pollution impacts of reducing CO₂ emissions in China at a provincial level and concluded that climate mitigation investment in western regions

would yield more cost-effective reductions in reducing air pollution when compared to eastern regions.

4.1.4. Health impacts

In many cases, air pollution impacts (co-benefits) are used to estimate improvements in public health outcomes measured in terms of either reduction in mortality, morbidity, increased prevalence of diseases, and/or increased health costs. This estimation is supported by epidemiological research linking public health outcomes (impacts), such as reduced mortality, asthma or lower healthcare costs, to people's exposure to the concentration of air pollutants. In this typology we separate air pollution impacts (section 4.1.3) from health impacts (section 4.1.4) to improve the usability for policy analysis. The reason for this is that researchers may find it useful to be able to easily identify papers that have not estimated health benefits but have estimated pollution as the basis of further work either calculating the health benefits or calculating non-health co-benefits of reduced air pollution.

Some research indicates that even small increases in air pollution can lead to health costs. For example, one study focused on and conducted in the United States assessed in monetary terms the health co-benefits of reducing CO₂ emissions in transport, buildings and power sectors. Their findings indicated that reduced exposure to PM_{2.5} would reduce healthcare costs from \$6–\$30 billion depending on specific activities in the year 2020 (Balbus *et al* 2014). This estimation required linking air pollution impacts to health outcomes and healthcare costs.

Other studies included in the health impacts category report results in terms of improved health outcomes. For example, Crawford-Brown *et al* (2012) estimated that the ozone and particulate matter (PM)

reductions associated with climate change mitigation policies in Mexico would reduce mortality by around 3000 lives and 417 000 non-fatal diseases of cases per year by 2020. Bailis *et al* (2005) studied the mortality impacts and GHG emissions caused by household energy use in Africa. They found that gradual transitions to charcoal and petroleum fuels from wood would delay 1.0 million and 1.3 million deaths by the year 2030.

Finally, other studies focused on the health impact co-benefits of reducing non-CO₂ GHG emissions. For example, Anenberg *et al* (2012) used concentration-response functions to estimate worldwide air quality and health impact co-benefits of policy measures controlling methane and black carbon.

Figure 6 shows in schematic form the relationship between the different outcomes reported by different papers and the classification of papers into the 'air pollution impacts' and 'health impacts' co-benefit categories. The figure shows that GHG mitigation policies can result in the reduction of air pollution. Data on reduced air pollution can be used through air dispersion models, for instance, to estimate ambient concentrations of air pollution. Concentration-response models can then be used to translate ambient concentrations of air pollution (included in the air pollution impact co-benefit) to estimate health impacts, such as avoided premature mortality. Some research then uses increased mortality and prevalence of non-fatal diseases outcomes to estimate health-related economic costs through approaches such as willingness to pay and quality-adjusted life year. Both the health effects, such as premature mortality, and health-related economic assessments are included in the health impact co-benefit.

4.1.5. Resource efficiency impacts

The resource efficiency impact includes energy efficiency, solid waste recycling, and resource/material use impacts.

Research has indicated that GHG mitigation policies can often lead to improved energy efficiency and increased resource utilization. For example, Garbuzova and Madlener (2012) concluded that GHG mitigation policies in Russia would contribute to increasing investments into equipment modernization in the Russian energy industry. As an example of research on resource efficiency impacts beyond energy efficiency, Kurniawan *et al* (2013) showed that the adoption of the Takakura home composting (THC) method in two cities (Surabaya and Kitakyushu) cooperatively resulted in reductions in GHG emission reductions and reduced municipal solid waste disposal volumes.

4.1.6. Conflict and disaster resilience impacts

GHG emission reductions have also been studied in terms of their ability to provide conflict and disaster resilience or to exacerbate conflicts and disaster vulnerability. For example, Huettner (2012) argued that

although the REDD+ program is expected to promote poverty alleviation, the marginalization of some local land users could lead to conflicts for land use if the policies are not well designed. Hsiang *et al* (2013) indicated that human conflict can be significantly influenced by climatic events, such as more extreme rainfall or warmer temperatures, which means that climate change mitigation could serve to reduce future interpersonal violence and intergroup conflict. O'Loughlin *et al* (2012) also examined the relationship between conflict risk and climate variability in East Africa during the period 1990–2009 and concluded that the precipitation and temperature effects are statistically significant.

Other work has indicated that GHG mitigation may also have impacts on our ability to manage the adverse impacts of climate change on geophysical, biological and socio-economic systems (IPCC 2007). In other words, some research has investigated the extent to which some GHG mitigation policies may be able to also improve climate adaptation. For example, Rahn *et al* (2014) investigated the threat that climate change imposed to coffee production and the livelihood of farmers in developing countries and concluded, using interviews and farm visits, that afforestation of degraded areas can produce the highest synergies between climate mitigation and adaptation. Lasco *et al* (2014) reviewed different studies on how small landholders adapt to climate risks in Asia and Africa and the impact of such adaptation measures on carbon sequestration. They concluded that compelling synergies between climate adaptation and mitigation can be obtained through agroforestry systems.

4.1.7. Distributional impacts

Energy access, energy poverty, poverty alleviation, social justice and equity are all included in the distributional impacts co-benefit. Casillas and Kammen (2012) argue that low-income people who depend on agriculture and weather patterns to earn a living will be most vulnerable to climate change impacts, and equity should be a central consideration for GHG mitigation strategies. Another example of research in this space is the work of Wang *et al* (2016) indicating that some climate change mitigation measures, such as carbon taxes, can make lower income groups being more affected if the tax revenue is not well used. Weber and Matthews (2008) linked American household consumption to their global carbon footprint and also indicated that climate mitigation policies such as carbon tax will have important impacts on people's income distributions.

4.1.8–4.1.10. Technological innovation, food security and energy security impacts

Other co-benefits of climate change mitigation efforts include technological innovation, food security, and energy security.

Developing countries, for example, can benefit from the spillovers of developing, adopting or adapting low carbon technologies as a result of their climate

change mitigation efforts, which have already benefitted from the effects of policies in industrialized countries (IPCC 2007). To achieve the goal of low-carbon power generation, some key determinants of upgrading wind power deployment in China are identified and thereby stimulating China's technology innovation in wind industry (Li 2010).

In the space of food security impacts, some research has found that more effective land use under the REDD+ program, especially in impoverished areas, can help improve food security (Palm *et al* 2010). Other research has focused on the energy security impacts of GHG mitigation in terms of the ability of particular policies not to reduce the dependence on external sources of energy but on the increased energy security that comes from a more resilient and diversified energy portfolio through low-carbon technologies and energy-efficiency improvements can help to realize the energy security goal for individual countries and regions (McCollum *et al* 2013).

Before moving on describing the typology of GHG mitigation sectors, it is important to highlight that some papers address more than one co-benefit, one sector, or one continent. In these situations, the papers were included in both categories.

4.2. Climate change mitigation sectors

The climate change mitigation sectors are categorized into the following eight types: the AFOLU, electricity, residential, transport, governmental, industry, marine and building sector.

The agriculture and transport sectors are the most frequently mentioned in the analysis of the keywords in the co-benefits publications. Publications with 'agriculture' as one of their keywords are often related to the AFOLU sector, which contributes to about 25% of anthropogenic GHG emissions globally (Bustamante *et al* 2014). The transport sector is also an important source for GHG emissions globally.

As mentioned before, the AFOLU sector refers to agriculture, forestry and other land use sector. The electricity sector includes power and energy sector. The residential sector includes heating, cooking, lighting, refrigeration, air conditioning, and using other appliances. The governmental sector contributes to GHG mitigation from the perspective of government. The industry sector includes sectors such as steel, cement and manufacturing sector. The marine sector includes fisheries and other marine related activities such as port investments, tourism, ocean iron fertilization, and marine shipping. The building sector includes commercial and residential buildings.

4.3. Geographic level

Publications are categorized in terms of their analysis according to the following four types of geographic scope: national, international, regional and city level. papers classified into the national level of analysis are studies that are focused on the context and co-benefits

that apply to one country at a national level, without breaking down information at the regional level within that country.

Regional level papers are those that conduct analysis of a region within a country (analysis that look at 'regions' defined by multiple countries are included in either the international or global category, as described below).

City level papers are those that look at one or several cities in either one country or various countries. And international level papers are those that incorporate analysis that include two or more countries, with a large fraction (70.0%) of them being analysis that are global—that look at countries around the world.

4.4. Geographic focus

In addition to providing insights about the geographic scope of the body of research on co-benefits, we also classified papers into the continent that was the main subject of their work: Europe, Asia, North America, Oceania, Africa and South America.

Some of the international level studies covered countries that were in more than one continent and, in some cases, we assigned the paper to the continents covered. However, in some cases, the international level studies covered the whole world. In such cases studies were classified as 'Global' in figure 8.

Before presenting the results of applying the typology, we will summarize the geographic level results from the keywords analysis. The most frequently studied countries in this research are China and India, which is not very surprising given that China and India are the two biggest developing countries in Asia, and the development of these two countries will play a major role in the world's ability to address the challenge of climate change.

4.5. Method classification

We classify the 1554 papers from the systematic review according to the main type of research method used. We group research methods (and thus papers) into three high-level categories: science and engineering methods, economic methods, social science methods, and other methods. Science and engineering methods include integrated assessment models (which, in contrast to optimization models, include models of the climate), optimization models (which include linear dynamic programming models, Markov model), simulation models (mainly agent based models and system dynamics models), life cycle assessment (LCA), concentration-response models, multi-criteria assessment, air dispersion models, and experimental approaches (conducting a scientific experiment). We divide economic methods into regression models, general equilibrium models, cost-benefit analysis, input-output models, partial equilibrium models and decomposition models. Social science methods include qualitative case study, literature review, surveys and interviews.

5. Discussion

We now summarize the insights that emerge from analyzing and visualizing the subset of 1554 papers on co-benefits according to the typology presented in section 4. We organize results presenting different combinations of the dimensions in table 1.

5.1. Research on particular co-benefits in different mitigation sectors

Figure 6 shows the correspondence between papers that cover ten different types of co-benefits with eight types of climate mitigation sectors. Some papers covered more than one type of co-benefits or sectors, and all types are counted in this study (this means that a paper will appear twice if it was focused on two co-benefits from one mitigation sector, for example). The ecosystem impact benefit type accounts for 19.1% of all papers, representing the type of co-benefit that was studied most widely, as measured by paper counts. The second co-benefit is economic activity, with 17.6%. Food security is the co-benefit type accounting for the smaller percentage (3.4%) of the papers reviewed. If air pollution impacts and health impacts are combined together, they constitute the largest proportion of the co-benefit papers (24.5%) instead of ecosystem impact.

The climate mitigation sector that has been the subject of most research is the AFOLU sector (31.6%), while the co-benefits of mitigation in the buildings sector has been the subject of the smallest percentage of publications (1.4%).

As we discuss below and is readily observable in figure 6, the analysis of different types of co-benefits is not equally-distributed across the mitigation sectors. The size of the research effort on a particular co-benefit from mitigation in a particular sector is denoted by the width of the flows going from the first to the second column in figure 7. The clearest example of that one would expect an uneven distribution of effort is that the co-benefit that has been the subject of most research, ecosystem impacts, is mostly analyzed as it applies to the AFOLU sector, since the AFOLU sector is more directly tied to ecosystems.

The key insight from the analysis in figure 6, however, is providing a sense of the co-benefits from particular mitigation sectors that have been more vs. less broadly studied. To some extent, having more papers in one type of co-benefit or for China is a function of how big the 'payoff' can be. However, to mobilize the public and policy makers to ramp up their GHG mitigation efforts it would be beneficial to have information on particular co-benefits and sectors in particular places even if, compared to the health cost of air pollution in China, their absolute value may be significantly smaller.

The discussion here and what follows identifies where there are opportunities to add to the evidence base by identifying and quantifying additional benefits

from mitigation activities in particular sectors, which could be useful for further mobilizing policy action.

5.1.1. Areas of significant research focus

We now discuss the combination of co-benefit types and mitigation sectors that have been the subject of the largest research effort so far.

The analysis of co-benefits in the form of ecosystem impacts in the AFOLU sector has been the focus of most research efforts, with a total of 222 papers. The second area of focus has been the assessment of economic activity in the AFOLU (92 papers) and electricity (87 papers) sectors. The third area of focus has been on co-benefits in the form of resource efficiency have a large focus in electricity (74) sector.

A lower level of activity has focused on: (a) air pollution on the electricity (60 papers) and transport (41 papers) sectors; (b) health impacts in the transport (54 papers), electricity (49 papers) and residential (42 papers) sectors; and (b) resource efficiency co-benefits from mitigation in the AFOLU (31 papers) sector. It was somewhat surprising that there has not been too much work on resource efficiency as a co-benefit of mitigation in the industry sector, given work on the circular economy.

Co-benefits of conflict and disaster resilience were often studied in AFOLU (60 papers) and residential sectors (25 papers), with distributional impacts being mainly studied as applied to the electricity (24 papers), residential (24 papers), and AFOLU (22 papers) sectors. Food security was substantially studied in AFOLU sector (43 papers) and energy security was primarily studied in electricity sector (37 papers).

5.1.2. Emerging areas or areas with little research

The emerging areas or areas with little research are defined by those areas that are covered by fewer than five papers, 65.5% of which are emerging papers published since 2013. Five papers is, of course, an arbitrary number of papers. As can be seen in figure 6, however, there are clearly some research areas that are the subject of much research and others in which research is much less frequent. This means that varying the threshold of the number of papers does not significantly affect our discussion of the emerging areas of research.

We found that the co-benefits of ecosystem impacts were studied the least as they applied to the transport sector (four papers). There were only three papers in each of the following combinations of co-benefits and mitigation sectors: economic activity in the marine sector; health impact in the building sector; distributional impact in the industry sector; and conflict and disaster resilience in the building sector. The study of economic activity in the building sector, and conflict and disaster resilience in the transport sector are both covered by two papers. There is only one paper in the study of health impact, distributional impact and air

pollutants in marine sector. Conflict and disaster resilience is not studied in the industry sector yet (zero papers). Co-benefits in the form of technological innovation were less frequent as they applied to the AFOLU (three papers) and residential (two papers) sectors. This is perhaps a reflection of the general (perhaps wrong) perception that there is not much new in terms of technology that can be done in both sectors.

The study of the food security co-benefit was scant as it applies to the residential (three papers), marine (two papers), electricity (two papers), industry (two papers), transport (one paper) and governmental (one paper) sectors. In turn, the study of energy security in the residential (three papers), building (two papers) and governmental sectors (two papers) is also very limited.

5.2. Research of particular co-benefits at different geographic levels

As shown in table 1, and implemented in figure 7, ten types of co-benefits and four types of geo-levels were identified and used to classify the database of co-benefit papers. Most of the co-benefit studies had an international level scope in their analysis, making up 37.5% of all the papers. Studies at the national level (namely, providing results of benefits that were studied in more than one country) made up 35.4% of the papers. 18.3% of the papers related to studies at the regional (sub-national) level. Finally, only 8.8% of the studies focused on co-benefits at a city level. We now discuss to what extent different types of co-benefits have been studied at these different levels.

5.2.1. Areas of significant research focus

Ecosystem impacts were studied most frequently at the international level (121 papers), national level (92 papers) and regional level (84 papers), while the study of co-benefits in the form of economic activity was primarily conducted at a national level (112 papers), international level (94 papers) and regional level (63 papers). The study of health impact co-benefits was focused on analysis at the international level (90 papers) and national level (68 papers). The focus on national-level analysis was also the key focus of the analysis of air pollutants (71 papers) and resource efficiency (64 papers).

5.2.2. Emerging areas or areas with little research

The emerging areas or areas with little research are defined by papers covering fewer than ten papers of a particular co-benefit in a particular geographic level. The emerging papers since 2013 accounted for 93.9% of the above papers. Co-benefits which were less studied from a city level perspective include distributional impacts (seven papers), energy security (seven papers), technological innovation (two papers) and food security (one paper). Technological innovation (six papers) and food

security (five papers) co-benefits were also both less studied at a regional level.

5.3. Research on different types of co-benefit by continent

As shown in table 1, and implemented in figure 8, ten types of co-benefits and six types of continents were identified and used to categorize the database of papers on co-benefits. Most of the co-benefits were studied globally or in multiple continents (namely, providing results of benefits internationally without making explicit what national and continental level benefits are) (30.5%), with the European continent being the one that is the subject of most research on co-benefits (20.9%). Co-benefits papers with a focus on Europe are followed by papers studying co-benefits in Asia (18.5%), and North America (10.7%). The continents that have been the subject of less research on co-benefit have been South America (7.8%), Oceania (6.0%) and Africa (5.5%).

5.3.1. Areas of significant research focus

Co-benefits of ecosystem impacts were primarily studied papers focused on multiple continents (96 papers), on Europe (71 papers), and on Oceania (35 papers). The study of co-benefits in the form of economic activity was mainly focused on papers covering multiple continents (81 papers), on Europe (54 papers) and on Asia (49 papers). Health impacts were mainly studied in papers evaluating multiple continents (81 papers) and Europe (44 papers), while air pollutants were most frequently studied in Asia (69 papers). Resource efficiency benefits were mostly covered by papers focused on Europe (45 papers), multiple continents (40 papers) and North America (30 papers).

5.3.2. Emerging areas or areas with little research

The study of a particular co-benefit in a particular continent was defined as emerging or with little research when no more than five papers focused on that space. The emerging papers published since 2013 accounted for 69.7% of these papers. Health impacts in South America and Africa have only been the subject of nine and three papers. Air pollution co-benefits were the focus of four papers on Africa and zero papers on Oceania.

Given that conflict and disaster resilience, resource efficiency, technological innovation, and food security were not as widely studied as other co-benefits, it is not surprising that there is little research on these co-benefits in the continents that have less research capacity. Conflict and disaster resilience co-benefits in South America were only studied in eight papers. Resource efficiency co-benefits in South America and Africa were only covered by six and three papers. The study of technological innovation on Africa (zero papers), Oceania (three papers) North America (three papers) and South America (three papers) was the subject of a small research effort. And, surprisingly, food

security covered nine, seven, six, five, and three papers in Asia, South America, Europe, Africa, and Oceania, plus one in North America, and energy security covered six, four, three, and three papers in South America, Africa, South America and Oceania respectively.

Distributional impacts in Oceania were studied in zero papers. Although more distributional impacts were studied in North America (six papers), the number is still small. Given recent political developments, it may be worthwhile to improve our understanding of the linkages between energy poverty and climate mitigation in North America.

In short, our understanding of a significant number of co-benefits in Africa, South America and Oceania is particularly poor, even when it comes to the co-benefits that have been most prevalently studied overall (namely, health, economic, and air pollution co-benefits).

5.4. Research on different types of co-benefit by method

As shown in table 1, and implemented in figure 9, ten types of co-benefits and three categories of methods were identified and used in the co-benefit papers. For each type of method, we also list the specific classification of each category in section 4.4.

Most of the papers investigating the co-benefits of climate change mitigation policy relied on social science methods (45.6%), followed by science and engineering methods (32.3%). Economic methods were used in 15.6% of the co-benefits papers. Within the category of social science methods, 50.8% of the papers are based on qualitative case studies, 25.1% on literature reviews, and 24.2% on surveys and/or interviews. We split social science methods into these three categories and show the breakdown of social science papers into those four categories in figure 9. Within the group of science and engineering methods, 23.5% of the papers use integrated assessment models, 22.9% optimization models without the integrated assessment (climate impact) component, 21.4% simulation models (e.g. system dynamics, agent based models, etc.), and 18.9% LCA tools. The breakdown of the science and engineering papers into eight specific categories is shown in the appendices (figure A4). In the category of economic methods, 32.0% of papers use regression (or econometric) models, 24.9% use CGE models, and 21.7% conduct a cost-benefit analysis. The breakdown of the economic methods into six specific categories is shown in the appendices (figure A5).

5.4.1. Methods of significant research focus

Social science methods are the predominant method in the co-benefit studies on ecosystem impact (154 papers), health impact (113 papers), conflict and disaster resilience (113 papers), distributional impact (57 papers), food security (26 papers). Science and engineering methods, and social science methods are almost equally used in the co-benefit studies on

economic activity (106 and 104 papers), resource efficiency (75 and 65 papers), air pollutants (70 and 51 papers), energy security (27 and 23 papers), and technology innovation (18 and 24 papers). A large fraction of the papers relying on qualitative case studies are studying the co-benefits of ecosystem impacts, conflict and disaster resilience.

Optimization models have largely been deployed to study the economic activity co-benefit (42 papers). In contrast, ecosystem impacts are mainly studied using simulation models (32 papers). Concentration-response models have been used to a large extent to study the co-benefit of health impact (21 papers), while (as expected) LCAs have been used to study resource efficiency (26 papers). Finally, the co-benefit of reduced air pollution has been studied using integrated assessment models (30 papers).

Moving on to the use of different economic methods, regression models have been the main tool used to study the impact of climate change mitigation on economic activity (22 papers) and ecosystem impacts (20 papers). General equilibrium models are more widely used to study air pollution (13 papers), distributional impacts (16 papers), and technological innovation (11 papers).

5.4.2. Methods with little research

To date, economic models are less used in co-benefit studies on energy security (14 papers), conflict and disaster resilience (9 papers), and food security (8 papers). The less frequently used economic models in research on co-benefits include input-output model (10.2%), partial equilibrium models (7.9%) and decomposition approaches (3.1%). It is important to note that, to a large extent, the ability of researchers to use different research methods depends on the type of co-benefit and on the data available.

The prevalence of research on particular co-benefits is likely to be driven by four key factors that are interdependent: (a) the expected size/relevance of that co-benefit; (b) the degree of confidence in the relationship between mitigation and a particular co-benefit, which is partly dependent on data availability; (c) the availability of research funding for a particular area; and (d) the research capacity and workforce in particular places. Even though in aggregate particular benefits (like health impacts) are large, if research ignores (or largely ignores) 'smaller' or 'more indirect' co-benefits, this may not be beneficial to society. First, even if in absolute terms particular benefits are large, at a smaller scale (e.g. at a local level), it may be the case that smaller benefits related to jobs or social inclusion could make the difference between more or less climate mitigation. In addition, one of the roles of research is to investigate linkages that could be important to society, even when there is a lot of uncertainty. Knowing about the small extent of work in particular benefits is helpful to identify gaps and possible areas in need of additional research effort and funding.

6. Conclusion

This study uses a systematic review, bibliometric analysis, network analysis, and a newly developed and implemented typology of co-benefits papers to improve our understanding of what we know about the co-benefits of mitigating greenhouse gas emissions.

The co-benefits of GHG mitigation have been identified as an increasingly important area that may help increase the political viability of stronger climate mitigation efforts by emphasizing benefits that may be closer to individual voters or firms and/or that may accrue to them in a shorter time frame. The identification of different types of co-benefits and dimensions helps inform future research by identifying areas with a lower level of effort.

Our systematic review resulted in a database of 1554 publications on co-benefits published between 2001 and 2016. The total publications and citations present an overall increasing trend over these years.

The frequency analysis of publication keywords provided insights on research hotspots, focused countries and sectors, and main research methods employed. Ecosystem impact, air pollution, health benefits, resource efficiency and disaster resilience are the most frequent keywords and China and India were the focus of the largest number of national studies. Agriculture and transport were the most frequently mentioned sectors. The main methodologies used to quantify co-benefits are forward looking integrated assessment models, and backward looking life-cycle assessment. The network analysis shows that research tends to be produced by teams working in close proximity, perhaps due to the fact that most papers are conducting national level analysis (as pointed out below).

The most important insights, however, stemmed from the inductive development of a typology of co-benefits papers from the database of 1554 papers resulting from the systematic review according to co-benefit type, mitigation sector, geographic level of analysis, and continent of focus and its subsequent application. We identify the combinations of co-benefits and mitigation sectors, co-benefits and geographic level, and co-benefits and continents that are the subject of around a handful of papers, pointing to opportunities for additional research.

We find that out of the ten types of co-benefits, the most frequently studied co-benefit is ecosystem impacts, followed by economic activity; energy security is the least studied co-benefit. The mitigation sector that has been most widely studied was AFOLU, and buildings the least. The study of co-benefits was conducted mostly at the national level, followed by international and regional level analysis. The number of co-benefit studies providing insights at the city level was very low, a finding that points to the need for additional research on co-benefits at this local level, given that some studies have argued that benefits that are 'closer to home' and closer in time may be more effective at

mobilizing public support for climate mitigation policies (Hoornweg 2011). While the largest number of studies analyzed co-benefits in more than one continent, most papers focused on Europe, with Oceania, Africa and South America being the focus of a very small number of papers. Most of the papers used social science methods for analysis, with qualitative case study method constituting the largest proportion. Within science and engineering methods, integrated assessment model, optimization model, simulation model and life cycle assessment are most frequently used tools. For economic methods, the most frequently used methods are regression models, general equilibrium models and cost-benefit analysis.

Another limitation of this work is that, since we develop the typology of co-benefits inductively, the typology only identifies co-benefit types, sectors, and methods that have been the subject of some research. In that sense, we do not reflect that there may be other co-benefits that have not been studied at all (at least as reflected in our systematic review). For example, we include the co-benefit of reduction of health impacts from reduced air pollution, but there may be additional co-benefits that we (and existing research) are not capturing in at least two related areas: (a) the reduction of health impacts from water and soil (as opposed to air) pollution; and (b) additional (non-health) benefits from reduced air pollution, such as increased economic activity. In that sense the development and implementation of the typology has also revealed that researchers need to continue working hard on determining co-benefits (positive or negative) of climate change mitigation. Socio-technical and environmental systems are indeed complex and if there is one thing we know for sure is that there are more interactions and effects than those we know about today. This should not be a cause for despair for researchers and policy makers, but rather, a call for additional understanding to be able to make (and get support for) the best informed decisions.

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Appendix

Table A1. The initial search string.

TS=((co-benefit* OR 'secondary benefit*' OR 'ancillary benefit*' OR 'side benefit*' OR 'collateral benefit*' OR 'associated benefit*' OR 'ancillary effect*' OR 'ancillary impact*' OR 'side effect*' OR 'health benefit*' OR co-control OR 'ancillary carbon benefit*' OR 'reduction benefit*' OR synergy OR 'adverse side effect' OR spillover OR trade-offs OR 'distributional aspect*' OR 'distributional effect*' OR 'mortality impact*' OR 'conflict impact*' OR 'social stability') AND ('climate change*' OR 'greenhouse gas*' OR 'GHG emission*' OR 'carbon emission*' OR 'CO₂' OR 'carbon dioxide'))

Table A2. The final search string.

TS=((co-benefit* OR 'secondary benefit*' OR 'ancillary benefit*' OR 'side benefit*' OR 'collateral benefit*' OR 'associated benefit*' OR 'ancillary effect*' OR 'ancillary impact*' OR 'side effect*' OR 'health benefit*' OR co-control OR 'ancillary carbon benefit*' OR 'reduction benefit*' OR synergy OR 'adverse side effect' OR spillover OR trade-offs OR 'distributional aspect*' OR 'distributional effect*' OR 'mortality impact*' OR 'conflict impact*' OR 'social stability') AND ('climate change*' OR 'greenhouse gas*' OR 'GHG emission*' OR 'carbon emission*' OR 'CO₂' OR 'carbon dioxide')) NOT TS=(cataly* OR reaction* OR bioreact* OR biocontrol OR temperature* OR metaboli* OR metal OR sediment* OR therm* OR insulation OR nano* OR chemi* OR biochemical OR laser* OR aneste* OR hyperoxia OR thoracoscopic OR batter* OR foam OR pyrolysis OR fluid OR ventilation OR radar OR dilute OR polyphenols OR slurry OR belowground OR host* OR DNA OR psychology OR antioxi* OR chemotherapy OR oxidation OR acidosis OR aerosol OR theophylline OR plasticity OR photosynthesis OR law OR Cournot OR palm oil OR warehouse OR antagonistic OR robust decision-making OR hypochlorite OR flux* OR manure OR RRE OR amine solvents OR phenolog* OR long-haul OR pareto OR RES-E OR bioethics OR abscisic OR bombus OR triazole OR shadow pricing OR flood probability OR South Tyrol OR CAFE OR postglacial OR palaeolakes OR malaria OR Landsat OR NDVI OR BMP OR DMM OR Rana sylvatica OR reroutes OR D-Allulose OR SDMs OR GWT OR analgesic OR Houtaomuga OR enzymes OR butterfly OR allometry OR arbuscular OR canopy OR PEB OR ECLSS OR Goldman Sachs OR DSM OR Free-Air OR Ketosteroid OR ANOVA OR Holocene OR weather-indexed OR vouchers OR clone OR Apostichopus OR anthocyanin OR VCAPS OR colonoscopy OR mutualism OR SDM OR cellular OR cod OR STIRPAT OR Salt-Marsh OR EnergyViz OR albedo OR salmon OR backburn OR lactate OR trend line OR MS-DCC-GARCH OR ontogeny OR Drosophila OR allele OR NPd OR Phenotypic OR Stringybark OR Counting carbon OR aflatoxin OR Arthritis OR SCE-UA OR epiphytic OR PFTs OR inter-temporal OR lemurs OR pastoral OR EEDS OR CACL OR naturalness-based corridor models OR VPSA OR SLA OR biogeochemical OR lake eutrophication OR Brassicaceae OR CART OR pleiospermum OR DBS OR MSFD OR dual-membrane OR catastrophic threats OR Delphi technique OR Sebastes melanops OR EOR OR WCPO OR trait loci OR range-edge OR Invasive syndrome OR bulk-scale OR Cartography OR EETGs OR Dinkelbach OR HAR-RV OR riparian plant OR EUPHAUSIA-SUPERBA OR Peromyscus leucopus OR Evolutionary games OR SimSphere OR Rana dalmatina tadpoles OR utero OR hormone OR Mercury in the Arctic OR Ensemble Kalman Filter OR K-selection OR exanthems OR kelp bed OR Paleoanthropology OR porcine OR Shoo OR Perla grandis OR Magnesium silicates OR NDWI OR FRMD OR WRF-Chem OR Mountland OR co-adoption OR RESCs OR HNS OR Yasuni-ITT OR SAGSO OR ITSFCPP OR metaheuristic OR polychaete OR Opioids OR FSTs OR tied ridges OR audience relevance OR pledge-and-review OR Nutrition-sensitive OR Shower flow limiter OR Re-exports OR Med-CORDEX OR KPIs OR FRAPP OR mediator OR MABs OR backtracking OR Angiosperms OR apoptosis OR hedgerows OR allopathic OR MEB OR pistillata OR fear appeals OR cyclodextrin OR APS OR tipping points OR dyschezia OR fatty-acid OR mosaic OR lipid OR ALM OR OMB OR Pinus pinea OR pasture-crop OR Canadensis OR illuminances OR CFLP OR NAMEA OR GARCH OR AUC OR sorghum OR entry deterrence OR Inter-Movement OR UNDP OR AFB OR xerophytic OR SE4ALL OR crystal OR papyrus OR NMBP OR agave OR Ktzi OR erythropoietic OR GLOBIS OR Insurers OR alkalinity OR UPRIIS OR matrix architecture OR Safety-Kleen OR armaments OR Birch OR ILIs OR electrolyzer OR cryospheric OR NFM OR Mendocinian OR palatability OR EAF OR Rasch OR MaxSEM OR functional fit OR SPM OR DLDD OR rigs-to-reefs OR ESG OR M&E OR EUA OR AST OR ILUC OR PICs OR graspable OR phylloclades OR MDP OR WETWin OR post-Annapolis OR syndemics OR HFNC OR RCTs OR LDCF OR OSI OR NOAA OR KPMG OR LCDS OR MS4 OR tridactyla OR HadGEM1 OR CUI OR DAF OR PEMS OR Aalborg OR CompasSus OR TLCAM OR IMSP OR FIEC-HYGARCH OR Q18 OR sanguine OR Rummy OR artisanal OR NPP OR CaCl₂ OR ENMs OR polymorphic OR macro-fauna OR Antarctic OR SP-FL OR refugia OR ESMs OR kraft OR MEMS OR phlegmatic OR carrier and shipper OR Zayandeh-Rud OR BRMP OR physico-economic OR Epthianura albifrons OR LCFS OR Spatial institutional spillover OR trade sanctions OR HABs OR lignocellulose OR LMWH OR FEAT OR rhythmanalysis OR DRR OR cataract OR LCP OR IWT OR cofiring OR VEPs OR Class-E OR faucets OR NCDs OR Semang OR turf-forming algae OR EMSs OR Intellectual Property OR Exchanging Goods and Damages OR Adaptive delta management OR Cyprus OR Zostera noltii OR learning coefficients OR beetles coleoptera carabidae OR cultural heritage OR collaborate decision making OR Telecoupled World OR Kirschbaum OR contrails OR inhaled corticosteroids OR polylactide OR gene flow OR AME OR re-contextualize OR GHGV OR SimCLIM OR Woodpecker OR whelk OR tristan-da-cunha OR WWTPs OR PCA OR EPP OR GSP OR OLG OR fungal OR IUCN OR Cobb-Douglas OR Strategic Theory of Regime OR facial rejuvenation OR folivore OR ZIS OR micro-cogeneration OR Type-approval OR POCP OR Brine production OR Kaya-Porter identity OR temporospatial change OR abalone haliotis-rubra OR IAASD OR GeoMIP OR IAEA OR aEuro OR triage OR Nursery Habitat Availability OR Crustose OR pentagon OR FRM OR MRI OR Pardosa lapponica OR MGLP OR Knightian OR Coweeta LTER OR dimethyl OR pinus-resinosa OR eddy viscosity OR frivolous OR Rio+20 OR HES OR TBL OR IMACLIM-R OR JNPT OR Chicken game OR diarrheal OR Precalcination OR CAAA OR ARDL OR Precautionary principle OR kerala OR WhC OR Erysimum OR growth dilution OR VGI OR individual MPAs OR Ayrshire OR pig-biogas-fish OR academic urbanism education OR democracy promotion OR EPANET OR Krishna OR small-scale fisheries OR time-tested OR grant competition OR SVCA OR food sovereignty OR WASP-IV OR Elk OR semiconductor OR ungulate OR suckler

Table A2. Continued

cow OR SMES OR GSMPI OR Risk-averse individuals OR Smart licensing OR cohesive principle OR anticonvulsants OR blackouts OR illustrative guide OR Simpson's paradox OR FCC spectrum auctions OR Clique OR Utsira OR FCV OR risk-tolerant strategies OR Biorefineries OR pathogen virulence OR membrane materials OR FORTRAN OR output-based allocation OR NW Pacific OR Inconsequentialism OR EACH-FOR OR flood risk dilemmas OR coal beds OR mesocarnivore OR carbonaceous fly-ash OR thromboangitis OR estuarine biotic invasions OR Oxyfuel OR Livestock genetic diversity OR Puget Sound OR Closed-loop chains OR re-greening OR Ku-ring-gai OR hypoxia OR Mombasa OR EBM OR WDM OR ELECTRE OR NGCC OR dermatology OR interwoven OR power asymmetries OR hazard-prone OR CEAP OR CGIAR OR BPS OR additive effects OR mcarthys OR D+D+D OR Tasmania OR powerful concept OR deltoidesxPopulus OR Seguimiento OR gill nets OR titania OR MAP-EVI OR Tranquillity OR UWS OR lenient OR cutting parameters OR PES-adaptation OR concrete-encased OR Ecohealth OR institutional inertia OR Cactus OR INRA-Theix OR steppe OR wildlife-friendly OR GOTILWA OR NRLP OR Loktak OR digital media OR subsidiarity OR caveats OR RF OR FTSE OR Rio Conventions OR Geotextiles OR EEA OR Intermediate disturbance hypothesis OR CLIFFS OR horizon scanning OR phenotype evolution OR Avian influenza OR Poignant OR co-delivery OR Succulent OR integrative science OR FESP OR T21 OR WDSs OR OBT OR radiotelemetry OR genetically-modified foods OR Business Ethics OR Comparative Physiology OR AGRRA OR Generalization errors OR IPAT equation OR priori beliefs OR CIESOL OR RSI OR HFCs OR plume stabilization OR Ruzi grass OR Formicidae OR Catchment Management Agencies OR LF OR SICA OR CFC OR Lankford OR Nephrology OR epistemic communities OR Larval connectivity OR patchy OR Denbury-Encore OR IFM OR activist groups OR mine-mouth OR Cryotherapy OR radiosonde OR Collaborative monitoring OR AD-DICE OR UIC OR Severity factor OR PBL OR Torres OR trampling OR Tchernobyl OR WEAP OR STACO OR Tourist types OR affirmative-action OR IDS OR Orkney OR acid mine drainage OR RUK OR cardiopulmonary bypass OR statistical expected values OR Cucurbita pepo OR iomass OR stratosphere OR endocrinology OR Chaetodon OR chlorine OR HAM OR pseudoscientific OR phosphorus surpluses OR trigeration solutions OR downplaying OR below-optimal OR lead poisoning OR WTO-accession OR BII OR telomerase OR herpetology OR triple-track OR relonics OR RTD OR Yukon OR Helms OR hedonic OR soft systems analysis OR Carraro OR Flavorcrest OR Quaternary conundrum OR Rio Grande Basin OR IPM OR deployable sensor OR AHP OR IPA OR edge effects OR laparoscopy OR Genomes OR dimorphism OR nasal OR ENTICE model OR WIAGEM OR hysteresis OR SSAB OR rice-fish OR SAV OR BTF OR Eigenvalue OR USDA OR UVR OR Ashmole OR substantive dialogue OR in-stream OR TGCs OR nutrition ecology OR Sepik OR Converging paradigms OR butterbur OR PTFs OR thalidomide OR pneumatic OR FOS OR Europeb OR West Nile OR surfactant OR citalopram OR holiday expenditure OR euthanasia OR Bhubaneswar OR prokinetic OR demethylation OR Eatwell OR 33 LAC OR FRMSs OR prelood OR grapevine OR Libyan OR In Vitro OR tala OR metamorphosis OR Juglans)

Note: After we have designed the search string to result in exactly the set of papers that cover co-benefits, we also need to introduce terms that excluded papers that, upon review, were not on topic. This involved choosing special words that would only exclude the papers that are irrelevant, and also involved testing many exclusion terms for each unsuitable paper to ensure that no other 'good/relevant' papers are excluded. This means that, although some words may seem odd, they are the ones that most precisely exclude irrelevant papers.

Table A3. The main language and publication type.

Publications in German, French, Polish and Italian account for 0.3%, 0.1%, 0.1% and 0.1% of the publications, respectively. The collected publications include 11 document types, as provided by the document type classification of Web of Science: articles (1367), reviews (144), proceedings papers (54), editorial materials (25), book chapters (9), letters (7), corrections (3), news items (3), book reviews (3), meeting abstracts (1) and reprints (1).

Table A4. Top ten journals in terms of their number of publications on co-benefits from GHG emissions mutation (2001–2016).

No.	Journal	Number of total publications in a particular journal	Number of publications on co-benefits	Ratio of co-benefit papers in one journal to all co-benefit papers %	Impact factor	Country
1	<i>Energy Policy</i>	7998	108	7.0	3.045	UK
2	<i>Climatic Change</i>	3246	39	2.5	3.344	Netherlands
3	<i>Global Environmental Change</i>	1296	37	2.4	5.679	UK
4	<i>Environmental Science & Policy</i>	1547	35	2.3	2.972	USA
5	<i>Applied Energy</i>	7859	34	2.2	5.746	UK
6	<i>Climate Policy</i>	833	33	2.1	1.980	UK
7	<i>Journal of Cleaner Production</i>	6654	33	2.1	4.959	USA
8	<i>Energy Economics</i>	2299	29	1.9	2.862	Netherlands
9	<i>Ecological Economics</i>	3906	25	1.8	3.227	Netherlands
10	<i>Environmental Science and Technology</i>	23 423	21	1.4	5.393	USA

Note: The impact factors in this table are the latest impact factor of each journal. The country refers to where the journal's publisher is located.

Table A5. Top 12 most prolific authors of publications during 2001–2016.

No.	Author	Country	Number of publications	Percentage %	Average citations ¹²
1	A Haines	UK	13	0.84	39.00
2	D P Van Vuuren	Netherlands	12	0.77	32.00
3	K Riahi	Austria	12	0.77	64.43
4	M Amann	Germany	10	0.64	15.80
5	Y Geng	China	10	0.64	14.33
6	M Herrero	Australia	10	0.64	14.88
7	Z Klimont	Austria	10	0.64	7.50
8	B A Bryan	Australia	9	0.58	10.22
9	P Smith	UK	9	0.58	25.00
10	A Markandya	Spain	8	0.52	22.00
11	T Masui	Japan	8	0.52	17.50
12	P Rafaj	Austria	8	0.52	26.6

Note: The most prolific author in this space, with 13 publications, was Dr Andrew Haines (London School of Hygiene and Tropical Medicine), with Dr Keywan Riahi (from the International Institute for Applied Systems Analysis, IIASA, in Austria) having the co-benefit publications with the largest average number of citations (64.43).

Table A6. Top 11 most productive institutions on co-benefits. The ranking was determined by the number of publications in the co-benefits sample with at least one author from the institution (2001–2016).

No.	Institute	Type	Country	Number of publications	Percentage %
1	Int. Institute for Applied Syst. Analysis	Non-governmental organization	Austria	49	3.2
2	University of California Berkeley	University	USA	39	2.5
3	University of Oxford	University	UK	33	2.1
4	Wageningen University	University	Netherlands	30	1.9
5	University of Cambridge	University	UK	28	1.8
6	Tsinghua University	University	China	27	1.7
7	University of Leeds	University	UK	27	1.7
8	University of Queensland	University	Australia	26	1.7
9	University of Utrecht	University	Netherlands	24	1.5
10	Natl Inst. Environmental Studies	Governmental organization	Japan	23	1.5
11	Imperial College (University of London)	University	UK	22	1.4

Table A7. Top 10 publications in the co-benefits database in terms of forward citations. The categorizations in the last three columns were conducted using the process described in section 2 with hand coding.

No.	Author/year	Journal	TC ^a	AC ^b	Co-benefit type	Sector	Geographic scope
1	(Riahi <i>et al</i> 2011)	<i>Climatic Change</i>	330	55.00	Air pollutants	Electricity	International
2	(Eakin and Luers 2006)	<i>Annual Review of Environment and Resources</i>	311	28.27	Disaster resilience	A review	International
3	(Woodcock <i>et al</i> 2009)	<i>The Lancet</i>	283	35.38	Health impact	Transport	City
4	(Fischer and Newell 2008)	<i>Journal of Environmental Economics and Management</i>	224	24.89	Technological spillover/innovation	Electricity	National
5	(Hartog <i>et al</i> 2010)	<i>Environmental Health Perspectives</i>	206	29.43	Health impact	Transport	International
6	(Chhatre and Agrawal 2009)	<i>PNAS</i>	198	24.75	Economic activity	Forest	International
7	(Lal 2006)	<i>Land Degradation & Development</i>	191	17.36	Economic activity	Agriculture	International
8	(Richards and Stokes 2004)	<i>Climatic Change</i>	176	13.54	Economic activity	AFOLU	International
9	(Haines <i>et al</i> 2010)	<i>The Lancet</i>	163	20.38	Health impact	Electricity, Transport, AFOLU	International
10	(Hill <i>et al</i> 2009)	<i>PNAS</i>	154	19.25	Health impact	Electricity	National

^a TC refers to total citations.

^b AC refers to average annual citations.

Note: As shown in table A7, Riahi *et al* (2011) has the largest number of cumulative citations (330) and annual average citations (55.0). This paper evaluates the co-benefits in terms of reductions in local air pollution from different global climate mitigation scenarios, with a particular focus on modest rates of energy intensity improvements. The second ranked paper by Eakin and Luers (2006) is a review identifying different types of vulnerabilities to climate change, emphasizing emerging consensus on the importance of equity and social justice issues. As previously mentioned, the analysis of forward citations is not a perfect measure of scientific impact for various reasons. This is evident in table A7 which, for instance, shows that no papers published after 2011 are in the top ten, a fact that can be explained by the simple reason that they have had less time to be cited. Thus, this analysis is only meant to be indicative of the areas covered by some of the co-benefits papers that have been more widely cited.

¹² Average citations here refer to the average citations for several of the author's co-benefits publications.

Table A8. Specific examples of some of the most commonly used methods.

Based on the analysis of keywords, the most frequently used methods are integrated assessment model and LCA. It is quite common to analyze the co-benefits of mitigating GHGs with integrated assessment models such as the Global Change Assessment Model, the UK Integrated Assessment Model and World Induced Technical Change Hybrid. One of the uses of integrated assessment models is to estimate the relationship between climate policies and changes in the natural system and socio-economic systems. Some of the co-benefits analyzed in studies relying on integrated assessment models include the impact of climate policies on crop yields, ecosystems, air pollution, human health and socio-economic influences, such as abatement costs, employment effects and energy security (Apsimon *et al* 2009, Chaturvedi and Shukla 2014, Oxley *et al* 2012).

LCA analysis appraises the environmental impacts related to all the phases of a product’s life from beginning to end. LCA analysis can be used to identify the major sectors that contribute to environmental consequences of a certain product, or to evaluate the environmental impacts of large-scale carbon capture and storage deployment (Liang *et al* 2013, Singh *et al* 2012).

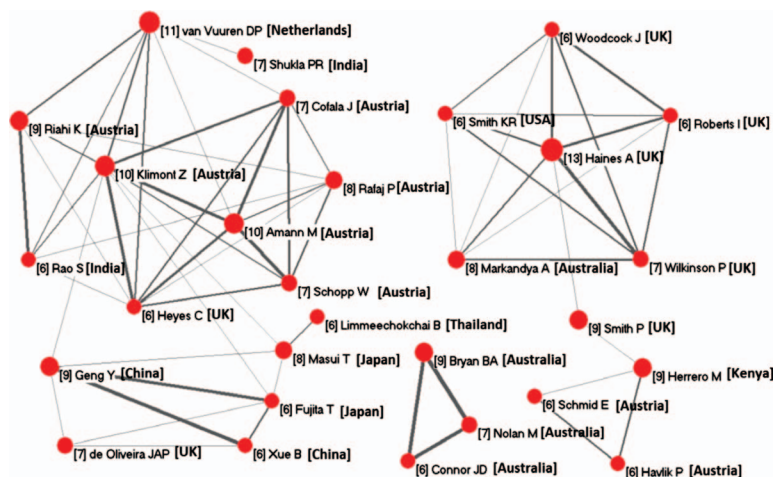


Figure A1. Cooperation among productive authors¹³. The size of the node denotes the number of publications that have that author, and the thickness of linkages among the nodes denotes how many times those authors have published together. Note: As shown in figure A1, the most collaborative author was Zbigniew Klimont at IIASA, who co-published with ten other authors. The analysis of cooperation across countries shows a large Austria and UK group of research. In addition, three authors from Australia cooperated closely with each other. The Chinese author Dr Yong Geng collaborated actively with Dr Bing Xue from China and Dr Tsuyoshi Fujita from Japan.

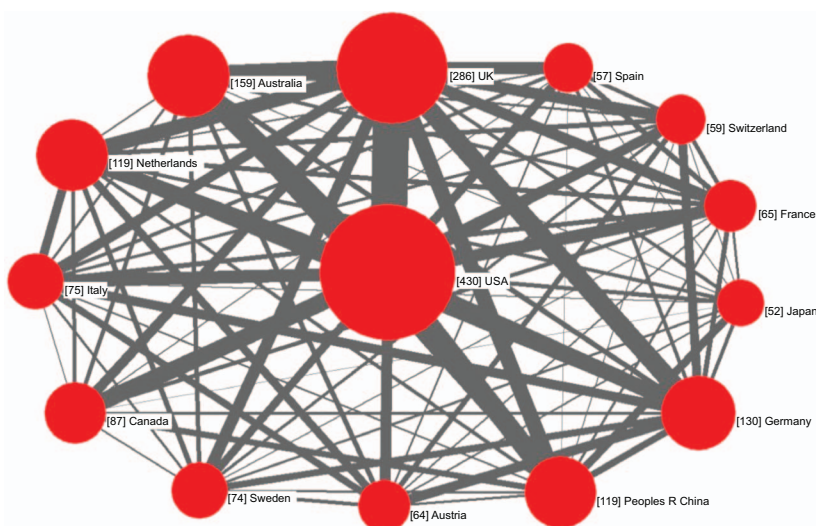
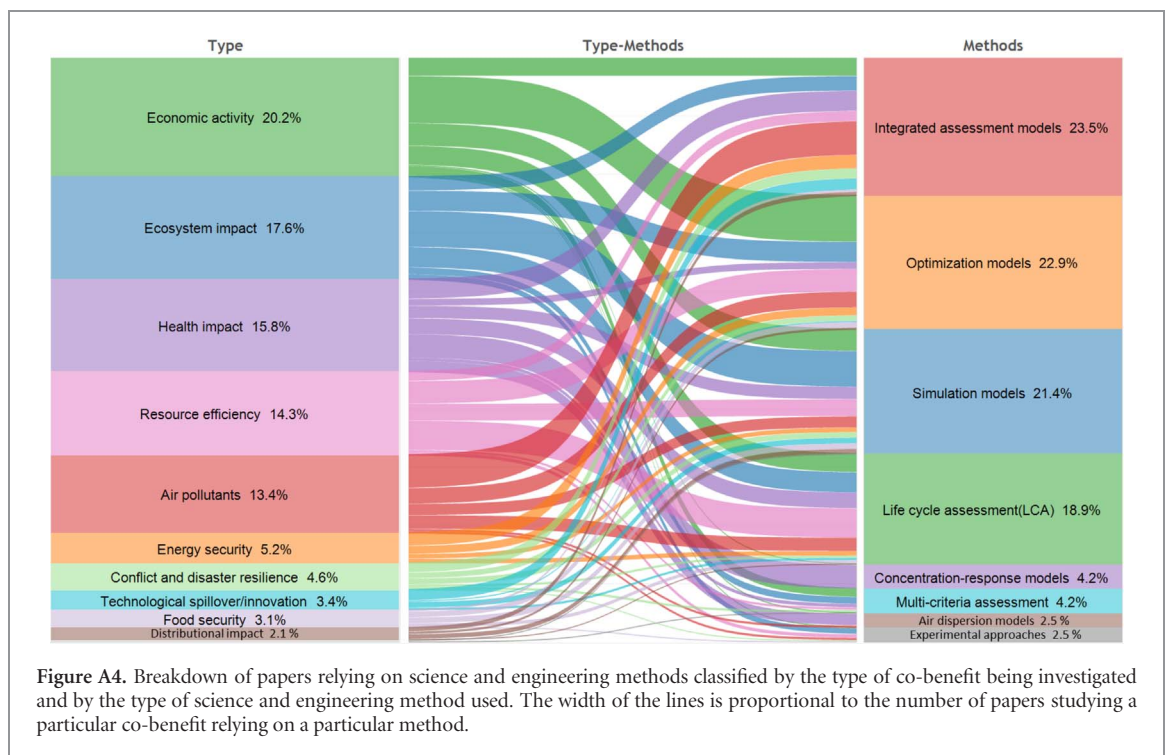
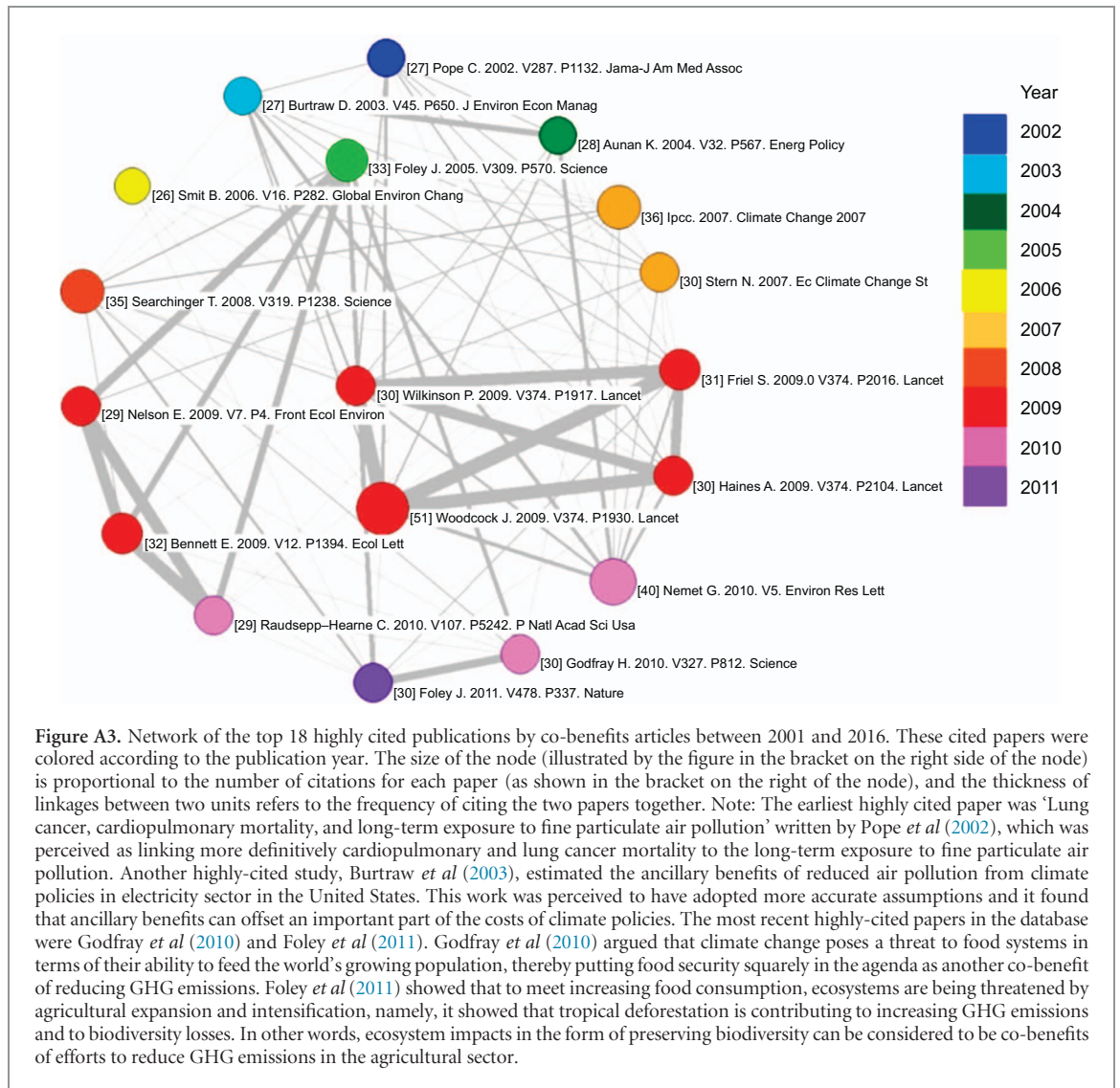
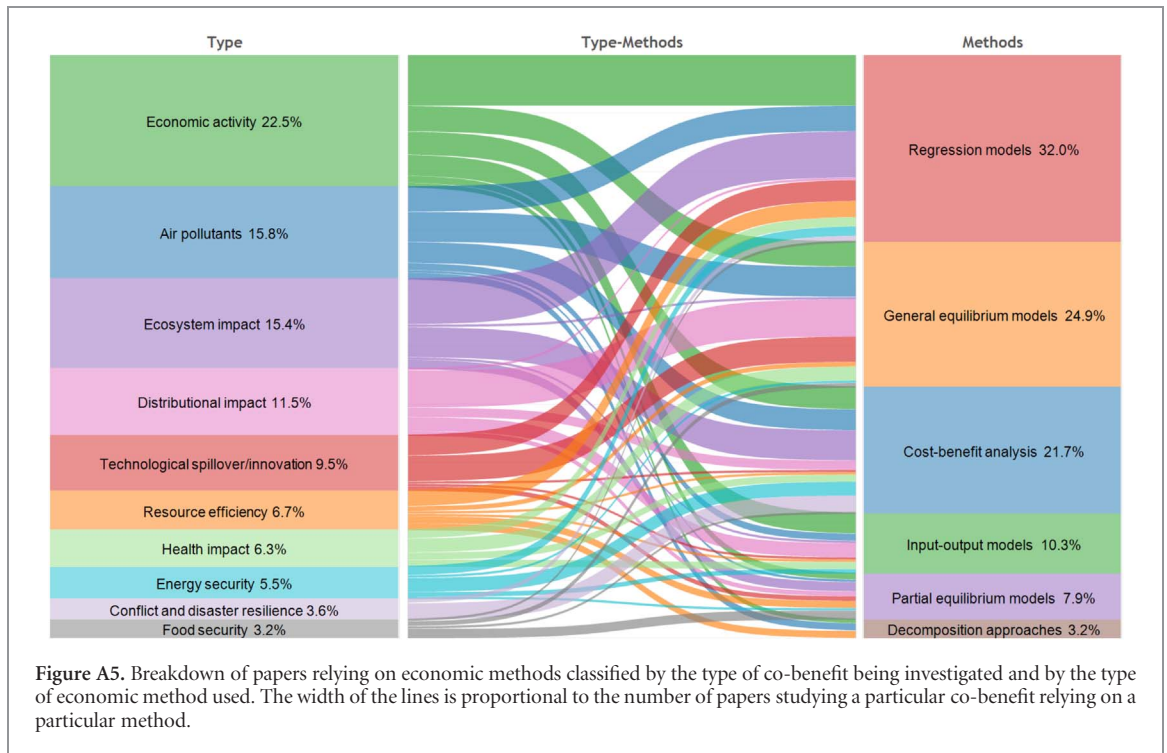


Figure A2. Cooperation among high-yielding countries. The size of the node implies the number of publications of each country, and the thickness of linkages among the units means the strength of cooperation. Note: figure A2 includes an analysis of joint publication grouping research institutions into countries with at least 50 publications. The research institutions in the US, in this case led by the University of California Berkeley (which is the most collaborative), showed a large number of collaborations with institutes in the UK, Australia, Germany, China, the Netherlands, and Canada.

¹³ For clearer illustration, the cooperation network of the authors who have more than 5 publications is presented.





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