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Jan C. Minx, Max Callaghan, William F. Lamb, Jennifer Garard and Ottmar Edenhofer

minx@mcc-berlin.net

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Learning about climate change solutions in the IPCC and beyond

Jan C. Minx[1,2,*], Max Callaghan[1], William F. Lamb[1], Jennifer Garard[1] and Ottmar Edenhofer[1,3,4]

[1] Mercator Research Institute on Global Commons and Climate Change, Torgauer Straße 12-15, 10829 Berlin, Germany
[2] Hertie School of Governance, Friedrichstrasse 180, 10117 Berlin, Germany
[3] Potsdam Institute for Climate Impact Research, Potsdam, Germany
[4] Department for the Economics of Climate Change, Technische Universität, Berlin, Germany
[*] corresponding author: minx@mcc-berlin.net

Abstract

There has been much debate about the assessment process of the Intergovernmental Panel on Climate Change (IPCC). Yet two of the most fundamental challenges that directly threaten the IPCC mandate have been largely neglected so far: the magnitude and rapid expansion of the climate change literature makes it increasingly impossible for the IPCC to conduct *comprehensive* and *transparent* assessments without major innovations in assessment practices and tools. Similarly, the structure, organization and scientific practices across the social sciences and humanities prohibit systematic learning on climate change solutions and increasingly limit the *policy-relevance* of IPCC assessments. We highlight the need for responses along three avenues to prepare the IPCC for continued success in the future: first, IPCC assessments must make better use of big-data methods and available computational power to assess the growing body of literature and ensure comprehensiveness; second, systematic review practices need to be enshrined into IPCC procedures to ensure adequate focus and transparency in its assessments; third, a synthetic research culture needs to be established in the social sciences and humanities in order to foster knowledge accumulation and learning on climate solutions in the future. As policymakers become more interested in understanding solutions, the future prospects of global environmental assessment enterprises will depend heavily on a successful transformation within the social sciences and humanities towards systematic knowledge generation. This article is part of a special issue on solution-oriented Global Environmental Assessments.

Keywords: climate change mitigation; IPCC; science-policy interactions; scientometrics; meta-analysis; systematic reviews

Introduction

It is the mandate of the Intergovernmental Panel on Climate Change (IPCC) "*to assess on a comprehensive, objective, open and transparent basis the scientific, technical and socio-economic information relevant to understanding the scientific basis of risk of human-induced climate change, its potential impacts and options for adaptation and mitigation* […]" (IPCC, 2013a: p.1). The assessment reports produced by the (IPCC) have provided a crucial scientific foundation for international climate policy negotiations under the United Nations Framework Convention on Climate Change (UNFCCC) and have had countless other impacts and influences on science and policy over the past 25 years.

Compiling an IPCC assessment requires a substantial collective effort by a diverse team of experts over many years to assemble, review and synthesize of the available scientific knowledge. To ensure that reports are compiled in accordance with the mandate, guidelines on conducting assessments are formally laid out in the IPCC's principles and procedures (IPCC, 2013a, 2013b). The authority of IPCC assessments has precipitated heated debates about its assessment procedures and their practical implementation. These discussions, on topics ranging from simple procedural matters to more thorny governance issues, have taken place both externally through academic publications as well as within the IPCC itself (IPCC, 2015c).

The first strand of these discussions is concerned with assessment procedures and practices in the broadest sense. Issues include how to deal with the growing burden on IPCC leadership and authors in a volunteer processes (Carraro et al., 2015; Schulte-Uebbing, Hansen, Hernández, & Winter, 2015; T. Stocker & Plattner, 2014; T. F. Stocker, 2013), the format of IPCC assessments (IPCC, 2015a, 2015b), the establishment of more systematic review practices to protect the organization from attacks in the long-run (Berrang-Ford, Pearce, & Ford, 2015; Petticrew & McCartney), and mechanisms to ensure better participation of authors from developing countries (Carraro et al., 2015; IPCC, 2015c; Petersen, Blackstock, & Morisetti, 2015).

A second strand of the debates emphasizes the need for a shift towards solution-oriented IPCC assessments to maintain policy-relevance in the future. 20 out of 32 submissions from governments to the task group on the future of the IPCC demanded more explicit focus on assessing solution options for climate policy (Kowarsch et al., 2016), including technological options, behavioral options, and in particular, policies (e.g., regulatory measures or market-based instruments) (IPCC, 2015a, 2015c). Disciplinary bias towards the natural sciences and economics (Bjurström & Polk, 2011; Carey, James, & Fuller, 2014; Corbera, Calvet-Mir, Hughes, & Paterson, 2015; Vasileiadou, Heimeriks, & Petersen, 2011), a lack of alignment with social science communities (D. Victor, 2015), geographical bias towards authors from and located in developed countries (Corbera et al., 2015), the lack of inclusion of practitioners (Viner & Howarth, 2014), a systematic exclusion of indigenous knowledge (Ford et al., 2016; Ford, Vanderbilt, & Berrang-Ford, 2012) and a dysfunctional Working Group structure (Carey et al., 2014; Carraro et al., 2015) have been identified as barriers that must be overcome to improve the assessment of solutions.

Questions about IPCC communications comprise the third strand of discussions. This broad debate covers the impact of the IPCC on scientific knowledge production (Vasileiadou et al., 2011), the readability of IPCC products (Barkemeyer, Dessai, Monge-Sanz, Renzi, & Napolitano, 2016; Field & Barros, 2015; Mach, Freeman, Mastrandrea, & Field, 2016), the media impact of IPCC assessments (Oneill, Williams, Kurz, Wiersma, & Boykoff, 2015) and the usefulness, transparency and perception

of IPCC uncertainty statements (Adler & Hirsch Hadorn, 2014; Budescu, Broomell, & Por, 2009; Budescu, Por, Broomell, & Smithson, 2014).

The fourth strand critically reflects on the IPCC as a science-policy interface. Recent discussions have focused on the politicization of IPCC approval sessions (Dubash, Fleurbaey, & Kartha, 2014; Edenhofer & Minx, 2014; Field & Barros, 2015; D. G. Victor, Gerlagh, & Baiocchi, 2014; Wible, 2014). There is also literature more generally concerned with the appropriate division of labor between science and policy and what this implies for assessment practices (Beck et al., 2014; Edenhofer & Kowarsch, 2015; Hulme, 2010, 2016).

While these discussions have provided important reflections, we argue that two additional challenges pivotal to a successful future for the IPCC have been largely overlooked in these debates. *First*, the large size and rapid expansion of the relevant scientific literature – henceforth referred to as 'big literature' phenomenon (Nunez-Mir, Iannone, Pijanowski, Kong, & Fei, 2016) – fundamentally challenges the IPCC's assessment practices and ultimately threatens the organization's ability to *comprehensively* and *transparently* assess the available literature. *Second*, a lack of progress in accumulating knowledge on climate solutions in the social sciences and humanities risks undermining the *policy-relevance* of IPCC reports even as policymakers increasingly demand robust evidence on how to solve the climate problem through mitigation and adaptation. Unless the IPCC addresses these challenges, its assessments will increasingly struggle to meet their mandate and will become progressively irrelevant in the future. In the remainder of the article we will analyze these two challenges and discuss some ways forward both within and external to the IPCC.

The literature explosion

In this section we employ scientometric methods to study literature growth in the field of climate change and the response of the IPCC to this problem so far. Scientometrics comprises an established set of methodologies to measure and analyze scientific research (Leydesdorff & Milojević, 2015). We follow the approach of Grieneisen and Zhang (2011) to track the number of publications on climate change as recorded in the Web of Science (WOS). The WOS database provides a wide range of peer-reviewed articles, books and conference proceedings across disciplines. For the period 1991-2009, our results closely match those of Grieneisen and Zhang (2011) as well as the results of a recent independent study by Haunschild et al. (2016). We extend this analysis further to 2016 and compare those results with the material used by the Intergovernmental Panel on Climate Change. A detailed description of our methodology and search query can be found in the Supplementary Material (SM).

The literature on climate change has grown exponentially over the last thirty years, as shown in Figure 1, turning IPCC assessments into an exercise in managing 'big literature.' While in the mid-1980's there were less than 1000 annual publications on climate change, we find more than 33,000 annual publications for the most recent year (2016). So far, there is no sign of a decline in this trend. With an annual rate of 16%, growth in publications on climate change has been substantially faster than the 4% growth observed for the scientific enterprise as whole. Overall, we find about 273,000 publications in WOS on the topic of climate change.

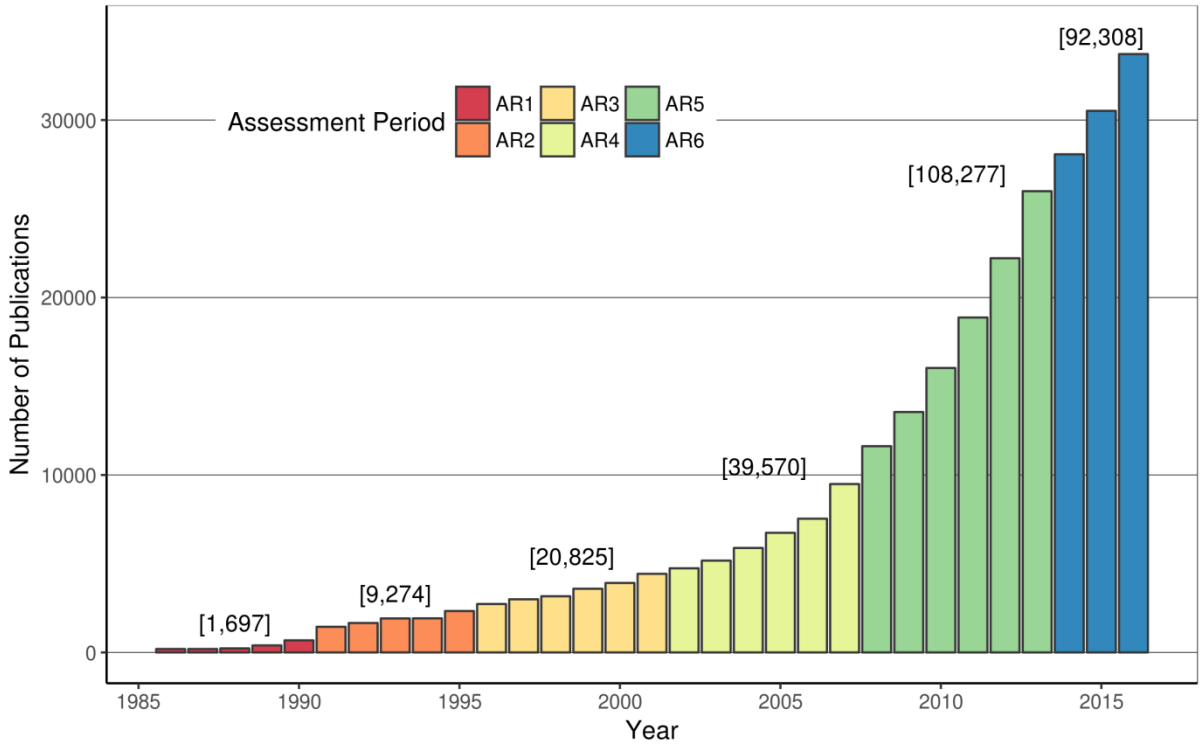

Figure 1 - Total number of scientific publications on climate change between 1986 and 2015 as recorded in the ISI Web of Science. The growth in the literature is exponential without a clear indication of levelling out. The six IPCC assessment cycles are identified by different colors.

The challenge for conducting comprehensive IPCC assessments has grown exponentially, too. As the IPCC should assess the most recent science, here we adopt the total number of new publications emerging across an assessment cycle as a rough approximation of this challenge. During the first assessment report (AR1) cycle, less than 1,500 studies on climate change appeared; for the most recent AR5 cycle, this number is approximately 110,000. In fact, the 30,000 new publications on climate change published in 2015 are almost equivalent to the entire body of literature available for the first three IPCC assessments, spanning the period 1988-2001, combined. We project a total of 200,000-300,000 new publications during the on-going AR6 cycle (lower and upper bounds defined by projections of zero growth and continued exponential growth, respectively). This is roughly the size of the entire WOS literature on climate change prior to 2014. We include this and additional analysis of the evolution of the disciplinary composition of the climate change literature in the SM.

To what extent has the IPCC been able to address this growing challenge and comprehensively review the most recent science? Figure 2 compares the number of publications on climate change published during each assessment cycle with the number of unique references made in the respective IPCC assessment reports. IPCC reports draw from a much wider body of literature comprising publications (a) about climate change not included in WoS (e.g. other peer-reviewed publications, most of the "grey literature" including books, reports etc.) or (b) not explicitly about climate change (and therefore not covered by our query) but relevant to its understanding. Because of this, the WoS estimates presented here provide an extremely conservative lower-bound estimate of the relevant literature, and the share of relevant literature covered by IPCC in Figure 2 is a highly optimistic upper-bound estimate, which nevertheless serves to show the trend over the five assessment periods.

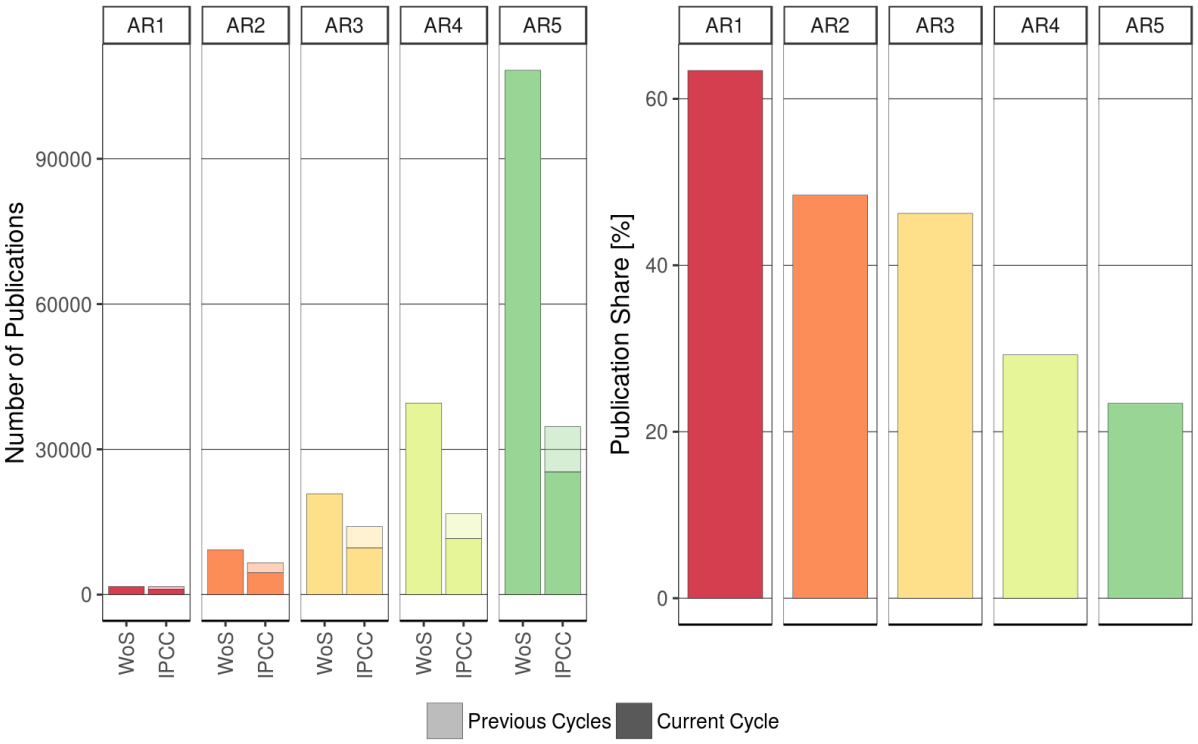

Figure 2 - The number of references in each assessment report has been declining rapidly as a proportion of relevant available literature over time. Left: Total number of scientific articles published during IPCC assessment cycle as recorded in the Web of Science and total number of unique references in the respective IPCC assessment. The light shaded portion of each bar represents unique references in IPCC reports to literature published before the start of the assessment cycle. Right: Ratio of unique reference count in each IPCC report to number of relevant available publications retrieved from Web of Science.

The first important aspect to note is that not only has the body of literature on climate change grown, but so has the number of unique citations made in IPCC reports: from AR1 to AR5 there has been a steady increase from about 1,600 to about 31,000 citations. Further, note that this is not only due to the increased length of each report, but also to an increase in citation density (citations per written page), from 1.6 citations per page in AR1, to 6.4 citations per page in AR5. IPCC authors have also been increasingly successful in focusing on the most recent science in IPCC assessments. Of the citations in the AR5 report, 72% refer to literature published in that cycle. This has risen gradually from 64% in AR1 (see SM for details).

However, despite all efforts, the ratio of references in IPCC reports to the newly emerging literature in WoS has been declining rapidly. While this publication share was 63% in AR1, it steadily declined to 23% by AR5. Despite this being a very optimistic estimate, it suggests that at least 80% of the most recent scientific literature could not be directly reviewed by IPCC authors in AR5 and was thus not included in the synthesis of scientific knowledge. Taken together, the sheer size of the current body of literature and the much higher share of publication coverage in earlier IPCC assessments suggest that reliance on expert judgement in selecting which of the literature to assess has become increasingly pronounced over time. The selection bias introduced by this expert selection and therefore the impact of 'big literature' on the assessment outcomes remains unclear and a discussion of procedural options to deal with it has so far been notably absent.

Accumulating knowledge across the IPCC

Knowledge generation for scientific policy advice

At the core of scientific assessments is the ambition to produce a knowledge map that can be used for policy-making (Edenhofer & Kowarsch, 2015). Yet, scientific assessments are only the last of three steps within a larger knowledge generation enterprise (Figure 3): (1) Knowledge production through individual research, i.e. expanding the boundaries of knowledge; (2) knowledge aggregation through systematic research synthesis, i.e. reconciling individual pieces of evidence and learning about the sources of variation to a specific policy question; (3) knowledge integration across a wider set of policy questions through global environmental assessments as performed by the IPCC in order to provide the basis for a more comprehensive mapping of policy alternatives.

Figure 3 highlights two important aspects. First, scientific assessments do not only rest on individual research, but importantly on efforts to accumulate the available evidence into discrete bodies of knowledge within the research communities. Second, not all types of evidence are equally suited for science-policy interactions. Science-policy exchanges should be based, wherever possible, on aggregated knowledge, where there is a sense for uncertainties, study quality and sources of variation across individual studies.

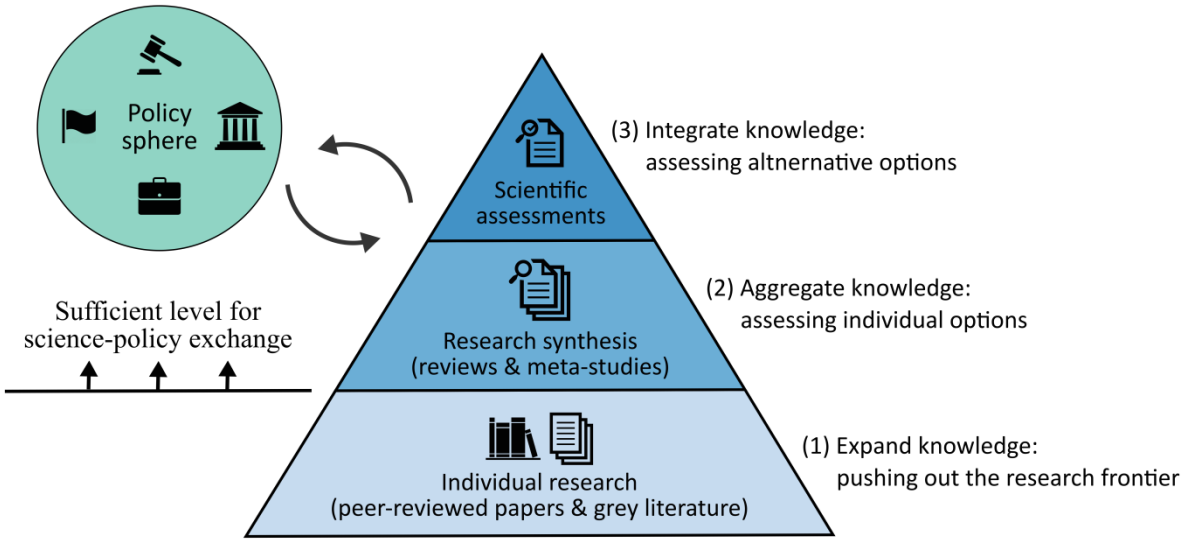

Figure 3 – Knowledge production for science-policy interactions

Uneven knowledge accumulation in the IPCC

The IPCC has done well in producing knowledge maps for understanding the physical science of climate change. Some of the fundamental questions, like “Is climate change man-made?”, have been answered over time with growing certainty by integrating multiple lines of evidence in a collective effort by the research community. This knowledge accumulation within the IPCC, in part driven by external pressures to strengthen the core science and legitimacy of climate change research, has been fundamental to progress in international climate policy negotiations (Bolin, 2007).

Similarly, there has also been some progress in accumulating knowledge and strengthening our understanding of climate solutions. For example, long-term emission reduction scenarios have been used to outline the social and technological solution space required to achieve different climate stabilization goals. By analyzing hundreds of climate change mitigation scenarios, it has been repeatedly established that, in principle, climate stabilization is possible with a reasonable set of mitigation technologies and at moderate economic costs (IPCC, 2001, 2007, 2014).

Areas where knowledge accumulation has taken place, and therefore also systematic learning, are typically characterized by scientific communities with a culture of research synthesis and collaborative research. For example, the Coupled Model Intercomparison Project (CMIP) systematically studies the outcomes of coupled atmosphere-ocean general circulation models (AOGCMs) based on a standard experimental protocol and had provided one important synthetic backbone in the climate sciences (e.g. Eyring et al., 2016). Similarly, the Integrated Assessment Consortium (IAMC) collected more than a thousand mitigation scenarios from modelling intercomparisons and individual activities (Krey et al., 2014). Together these studies formed a synthetic evidence base that was used in the IPCC assessment to clarify the key technological, economic and institutional requirements for limiting climate change to below 2°C, 2.5°C or 3°C (Clarke et al., 2014; IPCC, 2014).

Alongside technology studies and idealized climate change mitigation scenarios assessed by IPCC WGIII, there is a crucial role for social science research to assess the "real-world" practicalities of climate solutions. For building a compelling knowledge map for climate policy alternatives, it is necessary to understand which climate policies do and do not work under specific institutional arrangements, identify the conditions under which individuals or collectives cooperate, or establish how humans behave when faced with different types of pressures or incentives are (amongst many other issues addressed in the social sciences).

However, when it comes to the bulk of the IPCC-reviewed social science literature on climate solutions, progress in accumulating knowledge has been very limited. Table 1 provides an example of how typical high-level findings have evolved across the last three IPCC assessment reports, focusing on the Working Group III chapters on policies and instruments and their respective executive summaries (IPCC, 2001, 2007, 2014). Three important observations can be made:

- A clear evolution in the findings over time is lacking, which supports our claim that knowledge has failed to accumulate. In certain cases, there is some variation regarding a fairly disjointed set of conditionalities surrounding the main finding, but this variation does not appear systematic, insofar as later statements make no reference to earlier IPCC assessments.
- The findings do not reveal a systematic assessment of the literature. Rather, a series of statements are derived from standard economic theory without reflection on underlying assumptions, without reference to alternative findings or potential emphases, and without comprehensively reviewing the theory based on empirical methods and 'real world' policy assessments.
- The statements are typically overly generalized or purely descriptive in nature with little policy relevance. This seems true for both the core of the findings as well as some of the surrounding conditionalities introduced, which tend to be generically regarded as important,

rather than specifically detailed in terms of their actual effects on the performance of policies and institutions.

Is knowledge accumulation possible in the social sciences?

As a result, 25 years after the first IPCC assessments and with a myriad of new climate and energy policies having been implemented around the world (Dubash, Hagemann, Höhne, & Upadhyaya, 2013; Somanathan et al., 2014), we know little more about which of these policies have worked to what extent and why. However, this is not fundamentally a problem of the IPCC and how it conducts its assessments. Instead, the problem seems to stem more generally from the social sciences, public policy and humanities, where a broader body of literature highlights problems with the successful aggregation of knowledge (e.g. Hunter & Schmidt, 1996; Ringquist, 2013; Van Slyke, O'Leary, & Kim, 2010).

The most fundamental of these discussions deals with whether the social sciences can produce scientific knowledge at all, i.e. are there more fundamental philosophical and methodological concerns about the possibility of progress in the social sciences. There is an old and highly complex debate about the epistemic status and progress of social science knowledge, particularly in comparison with knowledge generated by natural sciences (e.g. Risjord, 2014). It is still disputed whether or not there is progress in the social sciences, and, if so, whether this progress is more limited than in natural sciences (Rosenberg, 1995). While we cannot adequately review and assess all major topics and arguments in this philosophical debate, let us briefly discuss a few selected, wide-spread viewpoints.

One major concern often asserted when it comes to social science knowledge about (climate) policy options is that social sciences are allegedly highly value-laden, in contrast to insights from natural science. Therefore, according to this line of reasoning, knowledge cannot accumulate in the same way as in the (purportedly objective) natural sciences. Involving value judgements and normative assumptions is seen as problematic for social science-based policy advice, because value-laden research is still regarded as biased and subjective, thus posing a threat to both the scientific credibility and the political legitimacy of social science policy assessments, e.g. by the IPCC (Douglas, 2009; Kowarsch, 2016). However, as the literature on the philosophy of social sciences has shown, it is a mistake to believe that the reason we do not observe the same extent of knowledge accumulation in the social sciences as compared to natural sciences is due to the many normative assumptions involved. First, there are also a wide diversity of values – cognitive, epistemic, but also ethical values – implied in natural science research (Douglas, 2009). Second, following pragmatist philosophy, value-laden social science research on climate policy options can still come to objective and reliable results (Kowarsch, 2016). Thus, the extent to which social science is value-laden is not significantly different than the natural sciences, and integrating values in social scientific research does not imply that objective knowledge cannot be produced and, in theory, accumulate over time.

Besides this value issue, other concerns about social science research include, for instance, the significant complexity and uncertainty of social system dynamics. There is also an ongoing debate about whether the natural science concepts of “laws” and “causality” are appropriate for social science research, and to what extent. However, it is not clear whether the objects (i.e., subject matter) of social science research are actually more complex and uncertain (as often assumed) than the objects of natural science (Rosenberg, 1995). In fact, already twenty years ago comparisons of

quantitative evidence in particle physics and psychology found more variability in physics (Hedges, 1987).

Tools for systematic research synthesis

We argue that in fact, social sciences have just as high potential for learning and knowledge accumulation as natural sciences. However, there are still fundamental challenges. First, there is a tendency for the structure and organization of research in social sciences, public policy and humanities to emphasize a paradigm of solitary, individualistic research, rather than more collaborative, synthetic efforts. As a result, the scientific process in these fields generates diffuse rather than cumulative knowledge, with detrimental impacts for both social science and policy. Second, and related to the first point, social science research is too often centered on the generation and testing of new theories rather than using strong inference to test existing theories. Third, there is a lack of systematic application of the available tools for research synthesis and meta-analysis (see Box 1) in these domains in order to produce studies which explicitly aggregate knowledge (Ringquist, 2013).

Recently, some authors have highlighted the lack of empirical evidence used in the evaluation of policy instruments and institutions in WGIII AR5 (Carraro et al., 2015; Kowarsch, Flachsland, Jabbour, Garard, & Riousset, 2014). We argue that the other core problem with learning on solutions is a lack of synthetic research evidence available for and used in the assessment (Box 1). For example, in the entire WG3 AR5, there are only 29 publications that can be clearly identified as systematic reviews or meta-analyses[1] from their titles, and none within the three policy chapters (13, 14 & 15). Only a single high-level finding from the Summary for Policymakers – that mitigation policies may yield large health benefits – is partially supported by synthetic evidence from a systematic review in the underlying chapter (Ito, De Leon, & Lippmann, 2005; Ji, Cohan, & Bell, 2011). Unsurprisingly, this evidence comes from the field of health, where a synthetic research culture has been established over the last decades. Overall, we find that only 0.57% of the social-science based climate change publications can be clearly identified as systematic reviews (see SM). This supports findings by Berrang-Ford et al. (2015) in the field of adaptation research that highlight the very limited application of systematic review practices particularly in the social sciences. Unless there is a paradigm shift in social sciences towards using such systematic review tools as part of the daily scientific routine, there is little scope to meaningfully improve learning about climate solutions within the IPCC.

[1] Note that these studies should be easy to identify, as standard practice calls for including “systematic review” or “meta-analysis” in the paper title.

Formal research synthesis: systematic reviews and meta-analyses

There is a whole arsenal of tools for research synthesis - formal research on research results - that are subsumed under the headings of *systematic reviews* or *meta-analysis* to aggregate evidence into discrete bodies of knowledge by reconciling evidence and understanding sources of variation in a rigorous way.[2] They are all guided by the principles of transparency and reproducibility and include formal quantitative methods for aggregating statistical and experimental research (such as meta-analysis), methods to review qualitative theory and evidence (such as meta-ethnographies), as well as methods to compile mixed quantitative and qualitative evidence (such as realist reviews) (Berrang-Ford et al., 2015). Despite their differences systematic reviews all share some common features that distinguish them from traditional literature reviews. These tools follow a clear methodological protocol that involves the following steps: 1) clearly defining the research question; 2) systematically searching defined literature databases for a defined time period; 3) justifying and making a transparent selection of the literature; 4) assessing the quality of the selected evidence; and 5) synthesizing the evidence based on a clear and transparent method.

Box 1 - Formal research synthesis: systematic reviews and meta-analyses

[2] In fact, there is some debate about the appropriate meaning of the term meta-analysis. It is frequently applied to refer to a narrower set of statistical methods for research synthesis. Here we use the term more broadly, synonymous with systematic review.

Table 1 - Example findings on climate policies taken from the Summary for Policymakers from the last three Working Group III Assessment Reports (IPCC, 2001, 2007, 2014)

	AR3	AR4	AR5
Regulatory policies	"Energy-efficiency standards have reduced energy use in a growing number of countries… The main disadvantage of standards is that they can be inefficient, but efficiency can be improved if the standard focuses on the desired results and leaves as much flexibility as possible in the choice of how to achieve the results."	"Regulatory measures and standards generally provide some certainty of emissions levels, but their environmental effectiveness depends on their stringency. They may be preferable when information or other barriers prevent firms and consumers from responding to price signals (*high agreement, much evidence*)."	"Direct regulatory approaches and information measures are widely used, and are often environmentally effective, though debate remains on the extent of their environmental impacts and cost effectiveness (*medium evidence, medium agreement*)"
Carbon taxes	"Market-based instruments– principally domestic taxes and domestic tradable permit systems– are attractive to governments in many cases because they are efficient... When implementing a domestic emissions tax, policymakers must consider the collection point, the tax base, the variation or uniformity among sectors, the association with trade, employment, revenue, and the exact form of the mechanism. Each of these can influence the appropriate design of a domestic emissions tax, and political or other concerns are likely to play a role also."	"Taxes and charges are generally cost-effective, but they cannot guarantee a particular level of emissions, and they may be politically difficult to implement and, if necessary, adjust. As with regulations, their environmental effectiveness depends on stringency (*high agreement, much evidence*)."	"Carbon taxes have been implemented in some countries and—alongside technology and other policies—have contributed to decoupling of emissions from gross domestic product (GDP) (*high confidence*)… In some countries, high carbon and fuel taxes have been made politically feasible by refunding revenues or by lowering other taxes in an environmental fiscal reform".
Cap and trade	"Like taxes, [tradable] permit systems pose a number of design issues, including type of permit, sources included, point of compliance, and use of banking. To cover all sources with a single domestic permit regime is unlikely. The certainty provided by a tradable permit system that a given emission level for participating sources is achieved incurs the cost of uncertain permit prices (and hence compliance costs)."	"Tradable permits can establish a carbon price. The volume of allowed emissions determines the carbon price and the environmental effectiveness of this instrument, while the distribution of allowances can affect cost-effectiveness and competitiveness. Experience has shown that banking provisions can provide significant temporal flexibility (*high agreement, much evidence*). Uncertainty in the price of carbon makes it difficult to estimate the total cost of meeting emission reduction targets."	"Cap and trade systems for greenhouse gases are being established in a growing number of countries and regions (*limited evidence, medium agreement*). Their environmental effect has so far been limited because caps have either been loose or have not yet been binding. There appears to have been a tradeoff between the political feasibility and environmental effectiveness of these programmes, as well as between political feasibility and distributional equity in the allocation of permits. Greater environmental effectiveness through a tighter cap may be combined with a price ceiling that makes for political feasibility."
The policy context matters	"A growing literature demonstrates theoretically, and with numerical simulation models, that the economics of addressing GHG reduction targets with domestic policy instruments depends strongly on the choice of those instruments. The interaction of abatement costs with the existing tax structure and, more generally, with existing factor prices is important. Policies that generate revenues can be coupled with policy measures that improve the efficiency of the tax structure."	"For an environmentally effective and cost-effective instrument mix to be applied, there must be a good understanding of the environmental issue to be addressed, the links with other policy areas and the interactions between the different instruments in the mix. Applicability in specific countries, sectors and circumstances – particularly developing countries and economies in transition – can vary greatly, but may be enhanced when instruments are adapted to local circumstances (high agreement, much evidence)."	"Adding a mitigation policy to another may not necessarily enhance mitigation (high confidence)." "The design of institutions affects the choice and feasibility of policy options as well as the sustainable financing of climate change mitigation measures (limited evidence, medium agreement)." "The ability to undertake policy action requires information, knowledge, tools, and skills, and therefore capacity building is central both for mitigation and to the sustainable development agenda (medium evidence, high agreement)"

Discussion: global environmental assessments at a crossroads

The IPCC has been operating successfully at the science-policy interface for the last three decades and its assessment process has become a role model in the field of global environmental assessments. However, the research landscape and the demands on the organization have fundamentally changed. The literature explosion and the shift in interest towards solution-oriented assessments present new challenges which the IPCC will need to face in order to maintain its relevance and reputation.

In this paper we have argued that the IPCC increasingly struggles to keep up with the exponential growth in the climate change literature. It is important to stress that this big literature challenge is not unique to the IPCC and has to be faced by all global environmental assessment processes today. Our scientometric analysis limits our exploration of the scientific literature to what is reported by WOS, but IPCC procedures require even more comprehensiveness (IPCC, 2013b). Other relevant sources include: 1) peer-reviewed literature not listed by WOS; 2) non-peer-reviewed sources; 3) non-climate literature directly relevant for understanding important aspects of climate governance or policies such as studies on cooperative behavior of humans, decision-making under risk and uncertainty or drivers of behavioral change. The challenges posed by big literature will be much larger than suggested by the Figures here, but we expect them to be still within the same order of magnitude.

The big literature challenge poses a real threat to the credibility of IPCC assessments, because the sheer volume of annual publications has made complete or comprehensive assessments of the literature intractable under current assessment practices. This raises important questions around literature selection: Which of the more than 30,000 annual publications should be covered? Which questions should be addressed?[3] How should the evidence be synthesized given the varying quality of studies? So far, the IPCC has relied on expert judgement to address these questions. A reliance on expert judgment alone in the selection of literature becomes increasingly problematic as the share of literature that can be directly covered by an IPCC assessment continues to drop. In this manuscript we show that around 80% of the most recent scientific literature could not be directly reviewed by IPCC authors in AR5.

We believe there are at least two avenues for addressing the problem of selection bias in IPCC reports and protecting the IPCC against the allegation of cherry-picking evidence in the long-run. First, there is a real need for innovation in assessment practices. In times of big literature, scientific assessments need to be computer-assisted and apply big data methods to deal with the literature explosion. Initial and very basic research applications are starting to emerge (Minx, Lamb, Callaghan, Bornmann, & Fuss, 2017; Nunez-Mir et al., 2016), but much is to be learned from other fields (e.g. Bosco, Uggerslev, & Steel, 2014; Rajesh, Adler, Noémie, & David, 2016). Second, while current IPCC procedures do a good job of organizing inter alia organizing author selection, review processes and report approval at the science-policy interface, they do not provide guidance for dealing

[3] It is true that a scoping meeting stands at the beginning of each report cycle, which provides a proposed outline that is subsequently discussed, adjusted and approved by governments (IPCC, 2013b). This approved outline usually provides generic chapter and often section headings to scientists as structure for the assessment. This process facilitates a dialogue between scientists as suppliers and policymakers as users of IPCC assessments on the contents of the reports. However, the process is currently not efficient in formulating a set of clear policy questions that would guide the assessment process and allow for a reproducible and transparent research process.

transparently with the process of research synthesis. It is indispensable for the IPCC to bridge the procedural void and firmly establish systematic, meta-analytical review practices at the heart of IPCC assessments.

Bringing about the required changes in a complex organization like the IPCC is not trivial. However, the IPCC does not need to start from scratch. Organizations like the *Cochrane Collaboration* or the *Campbell Collaboration* have about 20 years of experience with the formalization of research synthesis and could provide expertise in this process. We think that at least four cornerstones of research synthesis would need to be firmly established, in a procedural manner, if the IPCC wants to meet its mandate in the future and provide "comprehensive, objective, open and transparent assessments":

1. **Define a transparent set of policy questions for IPCC assessments**: Unless such a limited set of policy questions is agreed upon any claims of *comprehensiveness*[4] in the assessment of the available literature are elusive in times where 200,000-300,000 new WOS studies (see SI) are projected for publication during the AR6 cycle. Operationally, this could be part of the formal scoping process or left as a task for IPCC authors after the scoping of the report.
2. **Identify all relevant literature through a systematic and reproducible search strategy:** Unless there is an explicit search strategy that involves all relevant literature databases and clearly outlines pre-defined criteria for including or excluding evidence, the IPCC will continue to be exposed to criticism of "cherry-picking" scientific evidence.
3. **Critically assess the quality of the available evidence:** IPCC evidence is currently qualified based on the calibrated uncertainty language (Mastrandrea et al., 2010). This puts an emphasis on the weight of evidence, while the assessment of the quality of evidence (and how this affects results), as is common practice in systematic reviews, remains largely opaque (Petticrew & McCartney, 2011).
4. **Use explicit, qualitative and quantitative methods of research synthesis**: Unless the IPCC requires the transparent use of available research synthesis tools, it will be impossible to develop rigorous and reproducible assessments of the relevant literature.

Preparing the IPCC for the future would involve a whole series of supplementary action. This includes a broadening of the IPCC authorship not only to involve more scholars from the social sciences and humanities, but also to include experts on research synthesis, scientometrics and computational linguistics among others. Such expertise could also be used to professionalize report scoping and author selection in times where it is impossible for individuals to have a full overview of the field and collaboration between large numbers of authors with diverse expertise is an absolute necessity. Moreover, it would be possible to systematically address problems of regional balance in the IPCC authorship by using data mining techniques for the identification of experts across regions with the required scientific credentials.

We have further argued that progress in accumulating knowledge in IPCC assessments has been uneven across different fields. While the cooperative and synthetic research approach in climate sciences and other modelling communities has ensured collective learning over time, the IPCC has struggled with pushing the frontier of knowledge on climate solutions, which has become the focus of member governments (Kowarsch et al., 2016). This threatens the policy-relevance of IPCC

[4] In fact, IPCC procedures even refer to *completeness* at one point, which can never be achieved and can only be understood as a guiding ambition.

assessments in the future. Given the state of international climate negotiations, it seems clear that unless the IPCC can make relevant progress in learning about climate change solutions, it may lose much of the significance it has gained over the past three decades.

Yet, the capacity of the IPCC to provide research synthesis within the assessment process is extremely limited. It is fundamentally dependent on the scientific communities to provide aggregated knowledge palatable for assessment. The simple point is that IPCC assessments are currently lacking these inputs when it comes to social science research on climate solutions. Hence, the ability of the IPCC to produce policy-relevant assessments fundamentally depends on changes in the structure and organization of climate change research in the social sciences, where systematic, collaborative, meta-analytical research efforts become part of the scientific routine.

It is impossible to say to what extent the "supply side" choices of social science researchers and failings by funding bodies and policymakers on the "demand side" have created the particular research culture in the social science. However, it is very clear that changes in the funding structure of social science research towards research synthesis are a precondition for changes in the scientific practice. The IPCC will also need to support this cultural shift towards more synthetic approach in the social sciences and engage into an intensive dialogue with the relevant scientific communities. At the end of the day, the IPCC has been most successful in areas where the scientific communities have been strongly organized. Key figures and research organizations in the social sciences and humanities need to be convinced that it is worthwhile to organize such a community process that aggregates knowledge on climate solutions in key areas using the available arsenal of meta-analytical tools.

Finally, we need to acknowledge that systematic review practices are no panacea in themselves. We know from fields where systematic review practices are routinely carried out that there are growing problems with misconduct and study quality (Ioannidis, 2016). These do not question the importance of formal research synthesis in the social sciences for improving scientific policy advice, but urge for structured learning on problem avoidance. Similarly, systematic review practices within the IPCC would make the job for authors even more laborious unless specific and precise research questions were formulated. However, whether this is politically feasible and how the required procedural changes can be implemented within the decision-making structure of the IPCC remains uncertain.

Despite all their shortcomings, IPCC assessments remain among the most rigorous ever conducted. If the IPCC manages to institute formalized procedures on the transparent synthesis of scientific literature and to increasingly accumulate knowledge on climate solutions, then it stands a good chance of maintaining its relevance and reputation in the future. Some of the necessary changes are substantial and will require time and patience. It is good news that there are role models for such transformations. Research in medicine, education and psychology have had to grapple with similar challenges many years ago, and successfully managed a cultural transition towards systematic research synthesis. This has fostered knowledge accumulation in these fields and firmly established systematic research synthesis as a credible basis for policy advice. We believe that this is the best way forward for assessments on climate change and other global environmental problems, in general, and on the exploration of solutions and creation of knowledge maps for policy in particular.

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