Università
Ca'Foscari
Venezia

Corso di Dottorato di ricerca in
Scienza e Gestione dei
Cambiamenti Climatici
ciclo 33

Tesi di Ricerca

Complex networks in adaptation and mitigation to climate change

SSD: SECS-P/06 ; FIS/02

Coordinatore del Dottorato
Prof.ssa Enrica De Cian

Supervisore
Dr. Jaroslav Mysiak

Supervisore cotutela
Prof. Carlo Carraro

Dottoranda
Francesca Larosa
Matricola: 956338

Verità Per Giulio Regeni

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

INTRODUCTION[1]

1. Motivation and research objectives

The fight to limit global warming below 2°C has never been more urgent [1]. Policy makers, businesses, researchers and the civil society at large are becoming progressively concerned about the future of the Planet. Bold moves are still far from being implemented, but efforts to decarbonize the atmosphere and live sustainably have been made. This should not come as a surprise: rather than being owners of our Earth, humans are just one of the many species populating it. The humankind interacts with nature but built a system that led to governing its complex phenomena.

It is precisely the complexity of the human-nature interaction that got my attention when I started my PhD journey. The connected forces impacting our life on the planet are constantly mutating as outcome of our activities. These only apparent chaotic dynamics seemed to me unattainable at first. Colleagues from diverse disciplines and various backgrounds presented their solutions and lens of interpretation to multiple questions the world was asking. Among others, some stroked me more: how can we survive in a changing climate? How can we enact the transition towards a sustainable future? How far can we innovate to improve the way we deal with so many complexity layers? Luckily, algorithms and open science were and are growing at unprecedented rate. Most and foremost, a tendency towards interdisciplinarity allows more interactions across different problems: methods developed within the physics and ecology push social sciences and economics a bit further. The big challenge of our time – fight climate change – has been and is requiring this flow.

The increasing need to cope with climate change is framed within socio-economic narratives and the values they represent. The conflicts I observed in the initial stages of my career became even more explicit as the world transitioned towards a "call for action". Different groups, sectoral interests and dynamics constantly articulate in the networks through which the diverse compartments of our society are organized. I felt the urgency to uncover how these networks work and organize in meta-structures to reduce the vulnerability of socio-ecological systems to climate change (i.e. adaptation) and to advance the transition towards a climate-proof society (i.e. mitigation). Furthermore, I nurtured a genuine curiosity around innovation to both climate change adaptation and mitigation to understand how interdisciplinary insights and inputs help creating a new generation of science-based tools.

[1] This chapter is derived from Larosa, F., Ameli, N., Rickman, J. and Kothari, S.. *Beyond standard economic approaches: complex networks in climate finance* (June 18, 2021). Available at SSRN: https://ssrn.com/abstract=3873739 or http://dx.doi.org/10.2139/ssrn.3873739

When asked about the most adequate approach to tackle the climate challenge from a societal and transformative perspective, I surveyed the available tools and realized that climate differs from other threats: it imposes economic costs beyond the standard action time. As such, it is "the tragedy of the horizon" [2]. Hence, traditional approaches - especially those derived from neoclassical economics – fail us in presence of systemic global transformations. Network models and complex systems theory represent a valid alternative. Networks constitute a beautiful unit of analysis. They describe reality embracing complexity, allowing agents to continuously reshape the world they create.

Networks are represented as patterns of interconnected things, may them be agents, processes, abstract concepts [3,4]. Their structure describes the complexity they contain: the presence of hubs indicate that some nodes are more central than others. There may also be natural splits in between highly connected regions, which flag dynamics across distant clusters. The study of networks also reveals important insights about the "connectedness" of a complex system. Network's components can be linked because of their inherent characteristics or rather because of their behavior. Individual actions produce outcomes in everyone's else and lead to the emergence of collective phenomena. Hence, networks allow the assessment of aggregate behavior by exploring the interconnected actions of the individual parts [5]. Networks help tackling the diffusion and contagion processes [6] and the mechanisms underlying the successful uptake of new ideas [7], technologies [8] and behaviors within a social network [9]. These aspects are essential to promote a transformative and climate-friendly society, to advance adaptation to climate change and to support innovation for mitigation.

Networks describe a systemic reality where agents organize and evolve. As such, they portray transformative processes rather than isolated and static states of the world. This ability has been recognized in social sciences literature about technical change [10,11], sociology [12], economics [13,14] and information theory [15,16], among others. Insights from these areas of enquiry shaped this thesis and brought complex networks approaches into the climate sciences sphere, tackling how information is processed through a network, how agents organize themselves to drive a just energy transition and how innovation for climate action is co-produced.

I began by reviewing the existing state of knowledge and empirical methodology used to unfold these problems. I touched upon social [17], economic [14,18] and computational complexity [19], innovation networks [20–22] and case-based complexity [23]. Rather than dealing with a scientific and well-defined discipline, I approached a "movement within science" [14]. Within its boundaries, this movement offered me the most adequate tools to dig into both the structure and the process that describe the real-world networks.

I focused on two characteristic aspects of networks: **how they organize** (*i.e.*, the structure of their interactions, or topology) to favour adaptation and mitigation processes **and if and to what extent its components are related** (*i.e.*, relatedness). The study of topology [3,4,24,25] matters to anticipate change and critical transitions (W. Brian Arthur, 2021; Scheffer et al., 2012). Network metrics measure the density of connections [27,28] and identify groups of agents clustered together in communities [29], hyper-linked nodes [30,31] and influential spreaders in diffusion processes [32,33]. Knowledge about these aspects contribute to building policy-relevant considerations and to design mechanisms to trigger the best practices and to connect with the most marginalised agents across and within groups.
Relatedness is tied to the process of knowledge diffusion [34,35] and found quite a success in trade [36] and product specialization [37,38]. In this thesis, relatedness is applied in a novel way and combined with economic complexity insights [39,40] and machine learning to textual inputs [41,42].

The use of complex networks in the climate sciences sphere is promising. Complex networks are used to predict extreme events [43,44] and climate variability [45–48]. They are also proved appropriate in monitoring the state of ecosystem services via the stability of species interactions [49,50]. Economists use complexity to tackle environmental performance of countries [51] to study the link between economic complexity, specialization and greenhouse gas emissions [52–54] and to analyse green technological inventions [55], among others [55]. Complex networks and network models have wide room for use to map the uptake of innovative solutions beyond the use of patent and R&D aggregate expenditure data that both present critical limitations [56–58]. They are gaining increasing success in the finance and insurance domain [32,33,59], where networks uncover the systemic risks that cascade events – often disasters – produce. These methods are far from being perfect. More has to be done to fully deal with stability of financial networks and their relationship with climate-related risks [60]. Networks and complexity-derived methods can also shed a light on the unequal impacts of different climate policies and on the interconnectedness between heterogeneous agents and consequences of diverse economic incentives[55,61].

Thanks to the development of powerful AI and machine learning algorithms, the application of networks is gaining success and new frontiers of applied network science are opening. The doctoral thesis aims at showing the application of these methodological innovations to inform policy design. In this thesis I apply network science to deconstruct complex topics in adaptation and mitigation to climate change. I provide deep explanations of simple features: I look specifically at how networks organise and how their components relate to each other. I focus on three niche areas of enquiry: climate services, climate finance and climate innovation. The choice of the areas is motivated by priorities recently identified by the scientific community [62]. We live in the knowledge economy era, where inputs are dematerialised. Information is key to drive decision-making. In the first chapter, I focus on climate services, which serve this need: they bring climate knowledge and data into existing workflows and contribute to science-informed actions. Climate services support adaptation through a user-centered approach. As such, they need to fit within users' needs and to be credible. Their scientific reputation and business models become essential factor for their acceptance.

Climate services are also part of the climate innovation landscape analysed in chapter three. The fight to limit global warming and to respect the Paris target requires breakthrough inventions and sustainable innovations in multiple areas with the support of interdisciplinary research[63]. The application of network science to innovation for climate sheds a light on the existing connections between priorities and underlines if and to what extent a research-practice gap exists. Moreover, it flags who is contributing to the development of disruptive technologies, informing policy about smart specialisation and knowledge creation.

The last area of application of this thesis is climate finance. As reinforced at COP26 in Glasgow, finance is a key transformative factor and enabler. While policy agrees to invest more money in climate action, research is still exploring to what extent financial flows are reaching the most vulnerable and how financial resources are used. In this thesis, I apply network science to finance for hydropower – the largest renewable energy technology supplier at global level – to study how co-investments evolved over the past century and to detect the most critical actors in forming partnerships to reach the most vulnerable.

By building in key scientific priorities, the doctoral thesis explores the applications of network methods in three areas of enquiry to answer the following questions:

1. How is scientific collaboration supporting the development of adaptation-oriented and information-led climate services at global level?
2. Is there an optimal organisation for investors in hydropower capable of driving a just and inclusive energy transition?
3. Is there a measurable research-action gap in the European climate innovation policy framework?

4. Does a "fit-for-purpose" business model for climate services exist to scale-up their market?

To address these questions, I use data from multiple sources. I utilise bibliographic records, financial transactions, panel data and information from semi-structured interviews. In every chapter, I apply complex networks as framework for the analysis. The ultimate purpose of every chapter and thesis as a whole has been and will always be to provide policy-relevant insights.

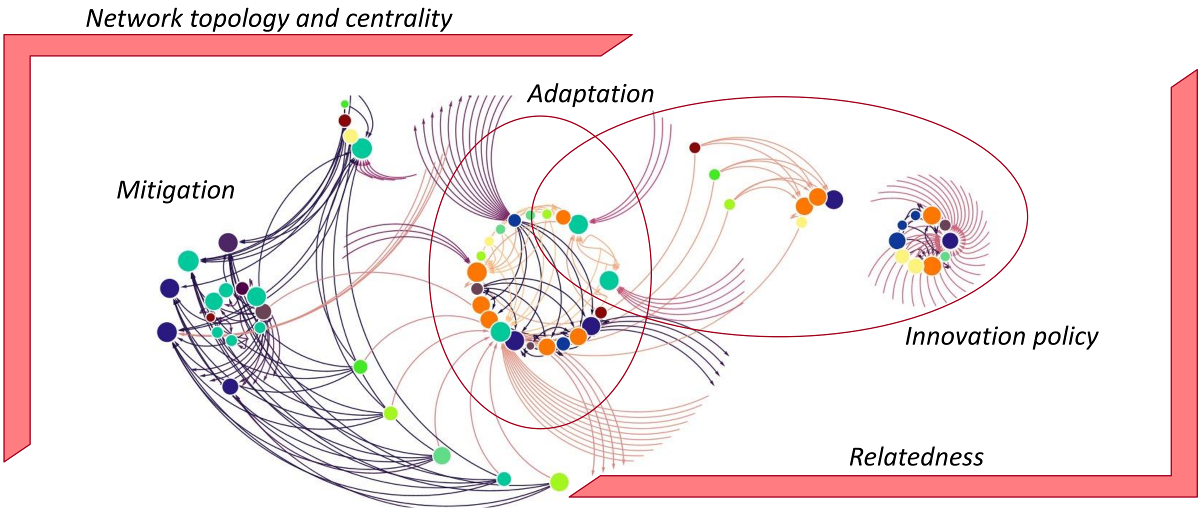


Figure 1 | Visual abstract of the thesis

2. Outline of the doctoral thesis

The thesis is organized as four core chapters and has an introductory chapter to frame the problem within the existing literature.

The first chapter explores the landscape of climate services by surveying peer-reviewed literature produced over the past decades. Climate services are user-tailored tools that transform raw climate data and observations into operational information. They democratize science and inform decisions at multiple levels of governance. Furthermore, they empower communities, businesses, organisations and countries by operationalizing knowledge that improve decisions. Climate services have been and are raising quickly across different sectors under the push of several international initiatives (*i.e.* The Global Framework for Climate Services and the European Roadmap for Climate Services among others). The demand for climate platforms, consulting services, data portals and information providers grow as the world recognizes the need to adapt. However, the field has developed disorderly with a plurality of definitions and approaches often conflicting with users' requirements. The market for these tools is fragmented and hard to monitor. At present, no database of climate services exists in Europe and beyond. No standard, label or professional association includes the prototypes and functional tools currently populating the market. Hence, the chapter uses a corpus of papers published between 1974 and 2018 to determine the network of individuals, institutions and countries active in this space. The chapter detects the characteristics of the community of climate services and measure the centrality of each actor as derived from a principal component analysis of 42 existing metrics. Finally, the chapter identifies the brokers, agents that facilitate the diffusion of information in their reference network.

The paper from which the chapter is derived was published in Environmental Research Letters (IF 5.026) in 2019 and since then (Figure 1) it became part of a "primarily adaptation-focused climate services literature" [64]. The work was presented on April 2018 in a dedicated webinar attended by approximately 90 participants and whose recording received 256 visualizations (as by June 2021). The original paper also won the Best Student Oral Communication award at the European Conference on Climate Change Adaptation (Lisbon, May 2019) contributing to raise interest in climate services.

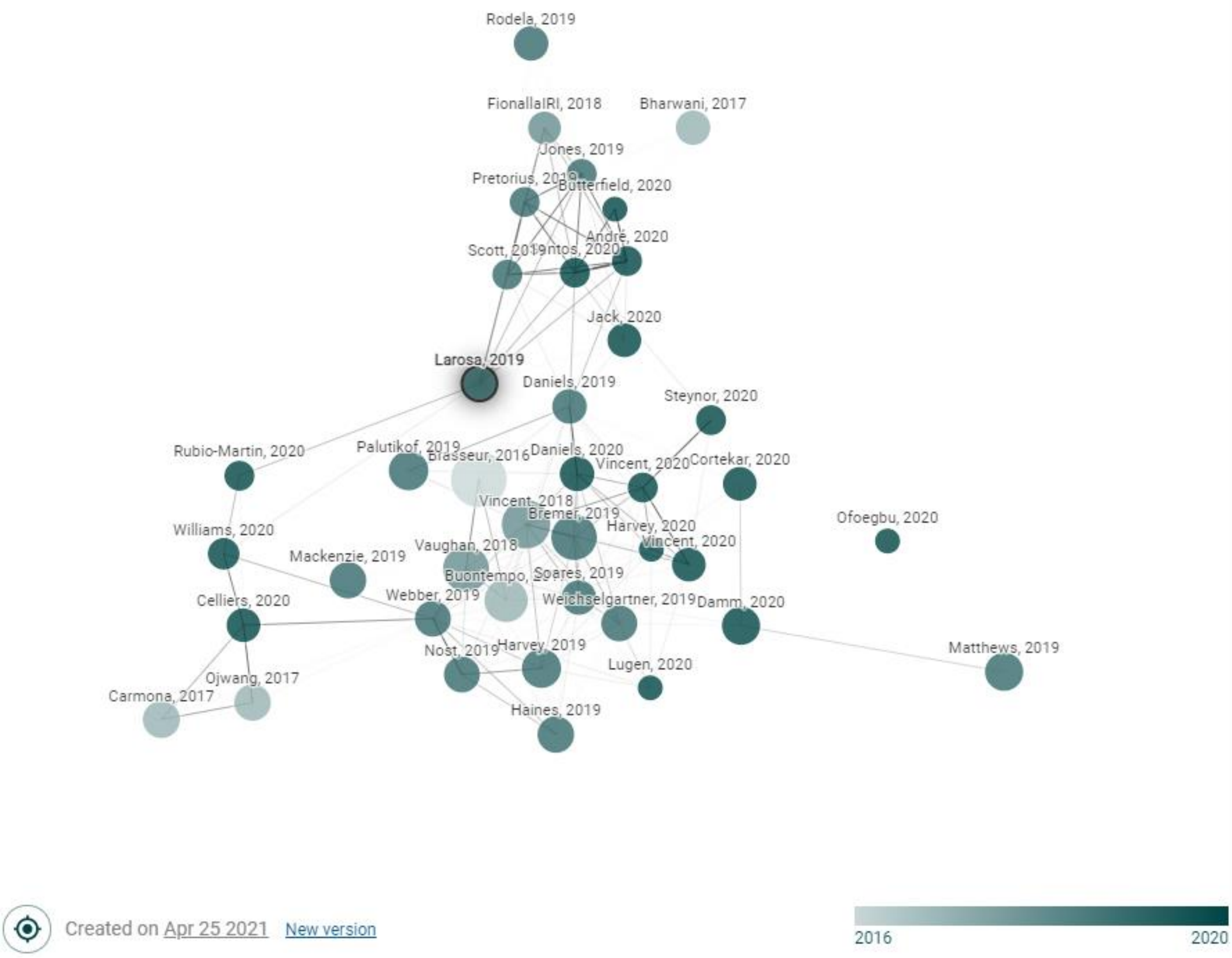


Figure 2 | The set of past and derived work of Larosa & Mysiak (2019) as by Connecting Papers

The second chapter of my thesis network approaches are used to study the importance of partnerships

in enacting a just energy transition. The focus is on investments in hydropower, as core renewable energy source especially in the most vulnerable countries. The chapter explores the system behind hydropower, investors' behaviour and how past co-investments contributed allocating finance at global level. Bloomberg New Energy Finance (BNEF) database is the main source of information to track public-private investments over the past century (1903-2020). Findings point towards strong investment home-bias, with continental players mostly interacting with counterparts in the same area of the world. Powerful exceptions are international organisations and multilateral banks which coinvest across the globe. They also tend to support low-income and fragile countries, meeting their mandate of sustainable development champions. Multilateral banks and international organisations are the most critical actors in enabling public-private co-investments: they activate partnerships with a wider diversity of investors within the network creating more opportunities for blended finance tools. The results of this chapter offer a novel perspective on finance for the energy transition: by looking at historical co-investment patterns, it derives implications on how countries locked in for the next decades. Inequality in financial resource access risks to compromise the global efforts to phase coal out. Developing nations, with growing energy demand and population rates, will require increased investment. Lessons from the past can inform optimal allocations in the future.
The paper from which the chapter is derived is currently under review in a top-ranked journal (IF 10.427) after being presented in a public webinar (April the 7th 2021) attended by approximately 80 people, in international conferences (the Fourth Northeast Regional Conference on Complex Systems, Boston, USA, March 2021) and internal webinars (UCL ISR Research Forum, September 2020).

The third chapter uses network science to offer policy-relevant insights to the European climate innovation sphere. Innovation is a key component to transform our productive systems and to equip our society with tools to adapt to new climatic conditions. Moving beyond invention, innovation operationalizes research in multiple domains to maximise the diffusion of new practices and solutions [65]. The creation of healthy research-action interfaces shifts useful ideas into operationalized knowledge. The main goal of the chapter is to quantify the existing gap between research and action using a novel framework that combines machine learning (Structural Topic Model) and network. The machine learning routine is applied to two layers of enquiry: the abstracts of a peer-reviewed bibliometric sample published between 1979 and 2020 and the corpus of EU-funded projects falling under FP6, FP7 and Horizon2020 programmes. The structural topics of the two samples are then used to build a a weighted network of themes on two separate layers., Weights correspond to the semantic distance of the bag of words in each topic. The research-action gap is measured by computing the cosine similarity of topics across multiple domains. Findings point towards notable differences in the composition of the two layers, especially for what relates to economic incentives, agricultural and industrial processes. There also exists a lose research-action connection in bioproducts, biotechnologies and risk assessment practices, where applications are still too few compared to the research insights. The chapter contributes to existing literature in innovation policy and flags how to operationalize more effectively research to achieve the newly launched mission-oriented European framework. Complex networks here are the key tool to assess the missed links between topics and the diverse structural connections between clusters of topics. Moreover, they highlight where interdisciplinarity should be strengthened to maximise the potentialities of Research & Development activities.

In the fourth and final chapter of the thesis networks are used to tackle business model innovation. The chapter is derived from a peer-reviewed article [66] and introduces a novel approach in the climate services literature. Rather than focusing on the climate services co-production process as many scholars [67–70], the chapter offers a business-oriented perspective to tackle where bottlenecks, limitations and barriers to deployment are. The diffusion of innovations depends on how business models - meant as firms' strategic choices to create, capture and share value within a value network - are employed. Innovation in business model, rather than product innovation only, has been proved useful for overcoming bottlenecks associated with development and diffusion of technologies. But only few studies have analysed how business models are used within the context of climate services. Business models as interrelated ecosystems have received quite attention from the literature [71] due to the importance of cycles and digital opportunities that enhance connections. Climate services are innovative and market-oriented tools aimed at democratizing operational information for a wide range of users. Despite their value, their uptake is still relatively lower than expected. A reason for that must be searched in the inadequacy of the business model climate services use. A "fit-for-purpose" business model that appreciates the diversity of factors constituting the ecosystem of players represents a strong signal to the market and introduces a new form of innovation in the system. The co-production provider-user process makes the definition of the most appropriate business model even more necessary.

In this chapter, complex networks are applied to interviews with climate services providers to tackle the business model they use. The business model is described as an ecosystem of strategies that realize the value proposition through the network of stakeholders involved in building a solid financial structure. The chapter presents these strategies as connected sets of codes derived from semi-structured interviews with 32 climate services at different development stages. The Business Model Canvas is the general framework to facilitate the data collection and analysis. The methodology combines Content and Network Analysis to code the interviews and to represents how business model aspects interact both within and across components. Findings stress the importance of the Value Network in which climate services operate. Also, they indicate a subscription, online-based infrastructure as the most widespread tool in reaching the target users. The creation of partnerships allows mutual learning opportunities and boosts the innovation behind these products. The focus on the graph giant component highlights the role of co-creation approach in generating direct and indirect incremental innovations while delivering seasonal forecasts and tailor-made services. The chapter calls for tighter link between business and climate-related aspects to enhance the importance of financial considerations around climate services provision.

Since its publication, the original paper received citations for both the methodology employed [72] and the content [73–75]. Moreover, it represents the first empirical contribution to business model innovation in climate services and it provides important insights for applied research in this space.

References

1. IPCC. *Climate Change 2021: The Physical Science Basis. Contribution of Working Group I to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change*. (2021).
2. Carney, M. Breaking the tragedy of the horizon-climate change and financial stability. (2015).
3. Barabasi, A.-L. *Network Science*. (Cambridge University Press, 2016).
4. Newman, M. E. J. The Structure and Function of Complex Networks. *Society for Industrial and Applied Mathematics* **45**, 167–256 (2003).
5. Easley, D. & Kleinberg, J. *Networks, Crowds, and Markets: Reasoning about a Highly Connected World*. (2010).
6. Guilbeault, D., Becker, J. & Centola, D. Complex Contagions: A Decade in Review. in *Spreading Dynamics in Social Systems* (2018).
7. Milli, L., Rossetti, G., Pedreschi, D. & Giannotti, F. Active and passive diffusion processes in complex networks. *Applied Network Science 2018 3:1* **3**, 1–15 (2018).
8. Wang, S., Zhao, J. & Yu, J. Seed selection for technology innovation diffusion in complex networks. *https://doi.org/10.1142/S0129183119500128* **30**, (2019).
9. Centola, D. An Experimental Study of Homophily in the Adoption of Health Behavior. *Science* **334**, 1269–1272 (2011).
10. Van Rijnsoever, F. J., Van Den Berg, J., Koch, J. & Hekkert, M. P. Smart innovation policy: How network position and project composition affect the diversity of an emerging technology. *Research Policy* **44**, 1094–1107 (2015).
11. Pugliese, E. *et al.* Unfolding the innovation system for the development of countries: coevolution of Science, Technology and Production. *Scientific Reports* **9**, 1–12 (2019).
12. Borgatti, S. P., Mehra, A., Brass, D. J. & Labianca, G. Network analysis in the social sciences. *Science* **323**, 892–5 (2009).
13. Arthur, W. B. Complexity, the Santa fe approach, and non-equilibrium economics. *History of economics ideas* **18**, 149–166 (2010).
14. Arthur, W. B. Foundations of complexity economics. *Nature Reviews Physics* vol. 3 136–145 (2021).
15. Lynn, C. W., Papadopoulos, L., Kahn, A. E. & Bassett, D. S. Human information processing in complex networks. *Nature Physics 2020 16:9* **16**, 965–973 (2020).
16. Karuza, E. A., Kahn, A. E. & Bassett, D. S. Human sensitivity to community structure is robust to topological variation. *Complexity* **2019**, (2019).
17. Castellani, B. & Hafferty, F. W. *Sociology and Complexity Science*. (2009).
18. Beinhocker, E. *The origin of wealth*. (2006).
19. Miller, J. H. & Page, S. E. *Complex Adaptive Systems: an introduction to computational models of social life*. (2007).
20. *Innovation in complex social systems*. (Routledge, 2013).
21. Arthur, W. B. The structure of invention. *Research Policy* **36**, 274–287 (2007).
22. Arthur, W. B. *The nature of technology: what it is and how it evolves*. (2009).
23. Lury, C. *et al. Routledge Handbook of Interdisciplinary Research Methods*. (2018).
24. Newman, M. *Networks*. (Oxford University Press, 2010). doi:10.1093/acprof:oso/9780199206650.001.0001.
25. Albert, R. & Barabási, A.-L. Statistical mechanics of complex networks. *Reviews of Modern Physics* **74**, (2002).
26. Scheffer, M. *et al.* Anticipating critical transitions. *Science* **338**, 344–348 (2012).
27. Robins, G. & Alexander, M. Small Worlds Among Interlocking Directors: Network Structure and Distance in Bipartite Graphs. *Computational & Mathematical Organization Theory* **10**, 69–94 (2004).

28. Watts, D. J. A simple model of global cascades on random networks. *Proceedings of the National Academy of Sciences* **99**, 5766–5771 (2002).
29. Fani, H. & Bagheri, E. Community detection in social networks. *Encyclopedia with Semantic Computing and Robotic Intelligence* **01**, 1630001 (2017).
30. Ashtiani, M. *et al.* Selection of most relevant centrality measures: A systematic survey on protein-protein interaction networks. *bioRxiv* (2017) doi:10.1101/149492.
31. Boccaletti, S., Latora, V., Moreno, Y., Chavez, M. & Hwang, D.-U. Complex networks: Structure and dynamics. *Physics Reports* **424**, 175–308 (2006).
32. Bardoscia, M. *et al.* The physics of financial networks. *Nature Reviews Physics 2021 3:7* **3**, 490–507 (2021).
33. Battiston, S., Mandel, A., Monasterolo, I., Schütze, F. & Visentin, G. A climate stress-test of the financial system. *Nature Climate Change* **7**, 283–288 (2017).
34. Cicerone, G., McCann, P. & Venhorst, V. A. Promoting regional growth and innovation: relatedness, revealed comparative advantage and the product space. *Journal of Economic Geography* **20**, 293–316 (2020).
35. Jaffe, A. B., Trajtenberg, M. & Henderson, R. Geographic localization of knowledge spillovers as evidenced by patent citations. *Quarterly Journal of Economics* **108**, 577–598 (1993).
36. Jun, B., Alshamsi, A., Gao, J. & Hidalgo, C. A. Bilateral relatedness: knowledge diffusion and the evolution of bilateral trade. *Journal of Evolutionary Economics 2019 30:2* **30**, 247–277 (2019).
37. D Bahar, R. H. C. H. Neighbors and the evolution of the comparative advantage of nations: Evidence of international knowledge diffusion? *J Int Econ* **92**, 111–123 (2014).
38. R Boschma, A. M. M. N. The emergence of new industries at the regional level in Spain: a proximity approach based on product relatedness. *Econ Geogr* **89**, 29–51 (2013).
39. Hausmann, R. *et al. The Atlas of Economic Complexity: Mapping Paths to Prosperity*. (MIT Press, 2013).
40. Hidalgo, C. A. & Hausmann, R. The building blocks of economic complexity. *Proceedings of the National Academy of Sciences* **106**, 10570–10575 (2009).
41. Blei, D. M. & Lafferty, J. D. A correlated topic model of Science. *The Annals of Applied Statistics* **1**, 17–35 (2007).
42. Airoldi, E. M., Blei, D. M., Erosheva, E. A. & Fienberg, S. E. *Handbook of Mixed Membership Models and Their Applications*. (2014).
43. Boers, N. *et al.* The South American rainfall dipole: A complex network analysis of extreme events. *Geophysical Research Letters* **41**, 7397–7405 (2014).
44. Donges, J. F., Zou, Y., Marwan, N. & Kurths, J. Complex networks in climate dynamics Comparing linear and nonlinear network construction methods. *Eur. Phys. J. Special Topics* **174**, 157–179 (2009).
45. Steinhaeuser, K., Chawla, N. V. & Ganguly, A. R. Comparing predictive power in climate data: Clustering matters. *Lecture Notes in Computer Science (including subseries Lecture Notes in Artificial Intelligence and Lecture Notes in Bioinformatics)* **6849 LNCS**, 39–55 (2011).
46. Steinhaeuser, K., Chawla, N. V & Ganguly, A. R. Complex networks in climate science. in *2010 Conference on Intelligent Data* 16–26 (2010).
47. Zhou, D., Gozolchiani, A., Ashkenazy, Y. & Havlin, S. Teleconnection Paths via Climate Network Direct Link Detection. *Physical Review Letters* **115**, 1–5 (2015).
48. Agarwal, A. *et al.* Network-based identification and characterization of teleconnections on different scales. *Scientific Reports* **9**, 1–12 (2019).
49. Keyes, A. A., McLaughlin, J. P., Barner, A. K. & Dee, L. E. An ecological network approach to predict ecosystem service vulnerability to species losses. *Nature Communications 2021 12:1* **12**, 1–11 (2021).

50. Landi, P., Minoarivelo, H. O., Brännström, Å., Hui, C. & Dieckmann, U. Complexity and stability of ecological networks: a review of the theory. *Population Ecology 2018 60:4* **60**, 319–345 (2018).
51. Boleti, E., Garas, A., Kyriakou, A. & Lapatinas, A. Economic Complexity and Environmental Performance: Evidence from a World Sample. *Environmental Modeling & Assessment 2021 26:3* **26**, 251–270 (2021).
52. Romero, J. P. & Gramkow, C. Economic complexity and greenhouse gas emissions. *World Development* **139**, 105317 (2021).
53. Neagu, O. & Teodoru, M. C. The Relationship between Economic Complexity, Energy Consumption Structure and Greenhouse Gas Emission: Heterogeneous Panel Evidence from the EU Countries. *Sustainability* **11**, (2019).
54. Can, M. & Gozgor, G. The impact of economic complexity on carbon emissions: evidence from France. *Environmental Science and Pollution Research* **24**, 16364–16370 (2017).
55. Balint, T. *et al.* Complexity and the Economics of Climate Change: A Survey and a Look Forward. *Ecological Economics* **138**, 252–265 (2017).
56. Popp, D. Economic analysis of scientific publications and implications for energy research and development. *Nature Energy* **1**, 16020 (2016).
57. Verdolini, E. & Galeotti, M. At home and abroad: An empirical analysis of innovation and diffusion in energy technologies. *Journal of Environmental Economics and Management* **61**, 119–134 (2011).
58. Popp, D., Hascic, I. & Medhi, N. Technology and the diffusion of renewable energy. *Energy Economics* **33**, 648–662 (2011).
59. Battiston, S. & Monasterolo, I. A Climate Risk Assessment of Sovereign Bonds' Portfolio. *SSRN Electronic Journal* (2019) doi:10.2139/ssrn.3376218.
60. Battiston, S., Monasterolo, I., Riahi, K. & van Ruijven, B. Accounting for finance is key for climate mitigation pathways. *SCIENCE* **372**, 918–920 (2021).
61. Emmerling, J. & Tavoni, M. Representing inequalities in integrated assessment modeling of climate change. *One Earth* **4**, 177–180 (2021).
62. Stainforth, D. A. & Calel, R. New priorities for climate science and climate economics in the 2020s. *Nature Communications* **11**, 3864 (2020).
63. The Royal Society. *Climate action: policy options and economic perspectives*. https://royalsociety.org/-/media/policy/projects/climate-change-science-solutions/climate-science-solutions-economics.pdf (2021).
64. Daniels, E., Bharwani, S., Gerger Swartling, Å., Vulturius, G. & Brandon, K. Refocusing the climate services lens: Introducing a framework for co-designing "transdisciplinary knowledge integration processes" to build climate resilience. *Climate Services* **19**, 100181 (2020).
65. Grubb, M. *Planetary Economics*. (Routledge, 2014).
66. Larosa, F. & Mysiak, J. Business models for climate services: An analysis. *Climate Services* **17**, (2020).
67. Brasseur, G. P. & Gallardo, L. Climate services: Lessons learned and future prospects. *Earth's Future* **4**, 79–89 (2016).
68. Buontempo, C., Hewitt, C. D., Doblas-Reyes, F. J. & Dessai, S. Climate service development, delivery and use in Europe at monthly to inter-annual timescales. *Climate Risk Management* **6**, 1–5 (2014).
69. Bruno Soares, M., Alexander, M. & Dessai, S. Sectoral use of climate information in Europe: A synoptic overview. *Climate Services* **9**, 5–20 (2018).
70. Vaughan, C. & Dessai, S. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* **5**, 587–603 (2014).
71. Shaw, D. R. & Allen, T. Studying innovation ecosystems using ecology theory.

Technological Forecasting and Social Change **136**, 88–102 (2018).
72. Stelzer, I. V, Sierawska, A., Buyx, A. & Simon, J. A network-based mixed methods approach to analyze current perspectives on personalized oncological medicine in Austria. *Journal of Personalized Medicine* **10**, 1–14 (2020).
73. Swart, R. *et al.* Reframing climate services to support municipal and regional planning. *Climate Services* **22**, (2021).
74. Perrels, A., Le, T.-T., Cortekar, J., Hoa, E. & Stegmaier, P. How much unnoticed merit is there in climate services? *Climate Services* **17**, (2020).
75. Jacob, D. Future trends in climate services. *Climate Change Management* 515–519 (2020) doi:10.1007/978-3-030-36875-3_26.

Mapping the landscape of Climate Services[2]

1. Introduction

Social and technological innovation is a vital part of adaptive capacity [1]. Innovation embedded in, or pursued by means of, climate services is conducive to a better management of climate risks [2]. Climate services entail "transformation of climate-related data into customized products such as projections, forecasts, information, trends, economic analysis, assessments (including technology assessment), counselling on best practices, development and evaluation of solutions and any other service in relation to climate that may be of use for the society at large"[3]. Several European and international initiatives have stimulated vibrant community: Third World Climate Conference (in 2009), the Climate Services Partnership (in 2011), the International Conference on Climate Services (in 2011), the Global Framework of Climate Services (in 2012), the European Roadmap for Climate Services (in 2015), and the Climate Services for Resilient Development Partnership (in 2017). Climate services can improve efficiency and speed innovative methods and processes in agriculture [4–6], urban planning [7,8], health [9,10], tourism [11,12], and other climate-sensitive sectors.

Climate services (i) are technology-intensive and draw on coding, protocols, systems and devices; (ii) employ action-driven research, connecting science, business and policy; (iii) share processes and workflows for climate-smart decisions. It is important not only trace the wealth of research outputs such as publications or patents, but also collaboration networks that have jointly produced these outputs. Co-authorship is a proxy of joint innovation and cooperation between institutions and experts. Network configuration makes it possible to represent co-authors or cooperating institutions as nodes, and innovation outputs as a network. Network analysis explore centrality and power relation driving innovation. Content analysis (CA) on the other hand sheds light on most salient concepts.

This chapter maps the landscape of research on climate services, offering a content-wise and spatially-explicit snapshot of what research on climate services looks like at global level. The work explores productivity patterns, time-evolution of fields of interest, and structural properties of co-authorship networks at individual, organisation and country level. The chapter uses a sample of 358 bibliographic records published between 1974 and 2018 and retrieved from the Scopus database in January 2019.

[2] This chapter is derived from Larosa, F. and Mysiak, J. 2019 *Environ. Res. Lett.* **14** 093006. https://doi.org/10.1088/1748-9326/ab304d.

Interactions of individual scholars and institutions are characterised combining Bibliometrics, Network Analysis and Content Analysis.

This work contributes to present literature in two ways. First, it provides a comprehensive mapping of actors and topics currently feeding research on climate services and, hence, climate innovation. Second, it offers an original methodological approach by including advanced statistical techniques to study node centrality, moving towards an objective assessment of the importance of a given agent. Furthermore, the chapter provides new methodological perspectives on how to analyse research by combining bibliometrics and network science in a highly sophisticated and replicable setting. The work is organised as follows. Section 2 provides the framework and introduces the data and the methods. Section 3 presents the results *(i)* giving insights on the conceptual structure through bibliometrics; *(ii)* elaborating about the social structure of interactions within the network of individuals, institutions and countries; *(iii)* assessing the most relevant concepts of the fields of interest over the considered timeframe. Section 4 concludes with the limitations of our approach and provides reflections on future extension.

2. Materials and methods

This chapter's framework combines bibliometrics, network and content analysis in a consistent approach. It aims at uncovering the conceptual and social structure of the network in which research is produced. The stepwise procedure allows to check and validate at multiple stages the quality of the analysis and the correctness of the results (Figure 3). The bibliographic sample was retrieved from the Elsevier's Scopus (www.scopus.com), a large abstract and citation database of peer-reviewed articles, querying a combination of keywords[3]. The same query run on Web of Science (www.webofknowledge.com) of Clarivate Analytics yield lower number of records. The query yielded records from 1974 until 2019. Non-relevant records were removed from the sample (see Supplementary Material).

Bibliometrics is used to describe the corpus of publications. Network Analysis and Content Analysis were, instead, deemed the most appropriate tools to assess the social and conceptual structure of the records included. Bibliometrics quantitatively assesses "the production, dissemination and use of recorder information" [13]. Bibliometrics has been used to study the evolution of a given field, as well as to characterize the polarization of different topics and institutions. In climate change domain, a

[3] "climate services" AND "Climate Services" AND "climate service" AND "Climate Service". We also run an alternative query ("climate service*") to check on the validity of our first search.

recent analysis based on 222,060 papers published between 1980 and 2014 identified an exponential increase and a strong presence of vulnerability and adaptation-related concepts among the most cited documents [14]. Research on impacts of climate change that goes beyond the natural sciences domain has intensified since 2005 and is quantitatively dominated by English-speaking countries [14]. Furthermore, bibliometrics is often deemed appropriate to assess the role of interdisciplinarity in fostering the creation of new ideas, by looking in-depth at the composition of research teams and at their expertise [15], as well as the exchanges between disciplines [16].

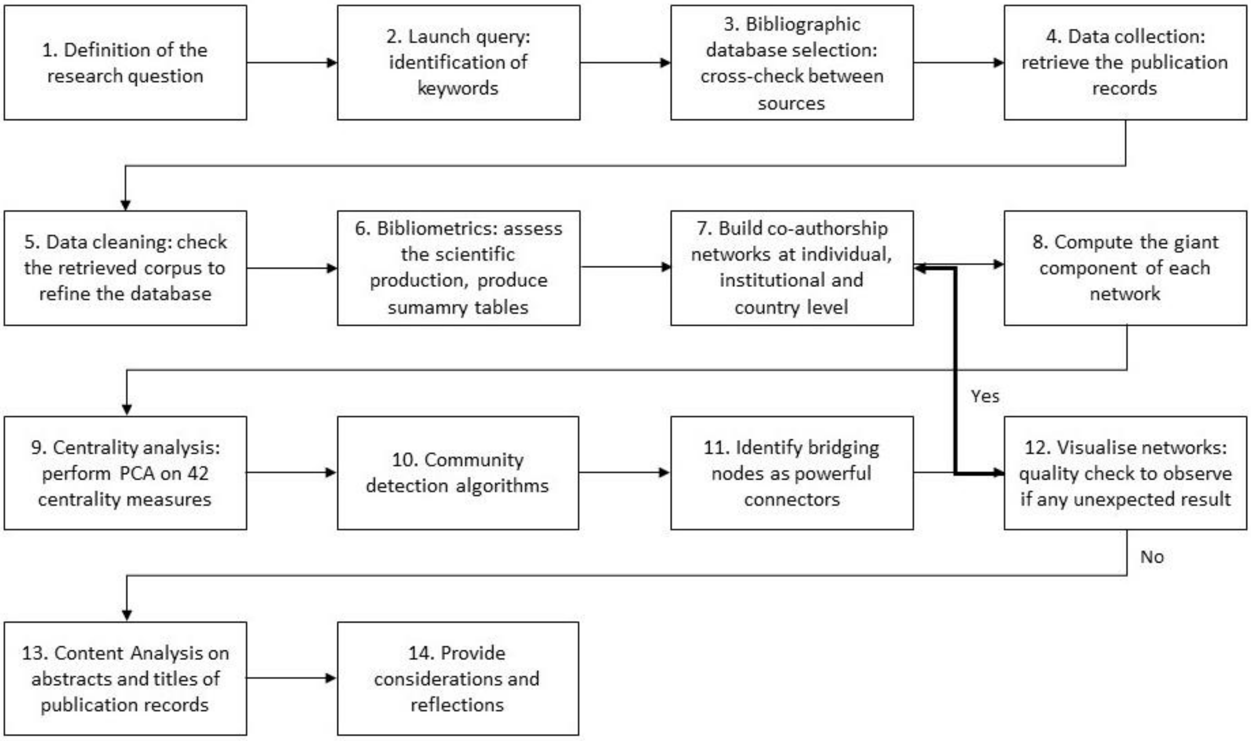


Figure 3 | A stepwise method to map research on climate services. The framework combines Bibliometrics, Network Analysis and Content Analysis and offers opportunities to revise and verify the process

To study the architecture and social structure of co-authorship, co-authorship relationships are derived at individual and institutional level to perform network analysis (NA). A network is a catalog of components $V(.)$ – the *nodes* or *vertices* – interacting within a system and connected through *links* or *edges* $E(.)$. A network is mathematically represented as a graph that can describe the complexity behind the individual node's behavior and the interaction between different nodes [17]. NA has been successfully applied to study the drivers of social consensus [18], as well as in analyzing social sciences [19] and the emergence of social dynamics [20]. In this chapter, agents are characterized on their "importance" (centrality) and their ability to influence others with respect to the giant component of the network. The giant component is the highest connected portion of the general graph. Due to the wealth of existing centrality measures, a Principal Component Analysis (PCA) on 42 metrics was deemed the most appropriate statistical technique to approach the data. Five and four main components in the individual scholar and institution and country case respectively explain more than 80% of the total variance (see Supplementary Material, chapter 1). Moved by the basic idea that "structure matters" [21–23], the chapter explores how the individual, institutional and country-level networks are built. Moreover, the chapter aims at detecting communities - meant as groups or clusters of nodes connected to each other than to nodes belonging to different groups – to understand how science and research on climate services move within the network of actors involved.

Community detection is vital when studying the structural features of a network, because it offers some practical insights. First, highly connected nodes could share interests or shared preferences. Second, agents within the same community may have a privileged access to information and opportunities. Therefore, the investigation of structural properties at network level can reveal some important information about the mechanisms behind collaboration and diffusion patterns. In the domain of climate services, the clear definition of what communities are is still largely missing. This has implications on the actual degrees of interdisciplinarity applied to the field: climate services require knowledge from climatology and physics, but also insights about information sciences, economics, business and sociology to deliver a fully science-based and tailor-made product. Hence, scholars may be involved in publications with a range of colleagues working in significantly diverse departments. Communities are nested and interlinked – often overlapping. The study of their structure provides knowledge about the content of research on climate services: depending on the bonds between scholars and institutions, insights from different disciplines are combined. The relevance of community detection has produced a wealth of algorithms and methods to facilitate the identification of different groups.

To obtain different community partitions, the chapter uses the Newman-Girvan algorithm, the Spectral community algorithm, the Greedy algorithm and the Louvain method separately (see Supplementary Material, chapter 1). The diverse outcomes are compared using modularity as criterion. This measure represents the "the fraction of the edges that fall within the given groups minus the expected fraction if edges were distributed at random" [24]. Higher values of modularity imply a better partition. The maximum modularity signals the top performing algorithm, hence the preferred community structure.

Finally, individual scholars are characterized based on their capacity to influence the network they are embedded in. Building on the idea of a world where "weak ties" are stronger than strong ones [25], brokers of information allow research insights on climate services to travel within the network. These "connectors" act through two channels: (i) if removed from the network, their absence cause a significant drop in the cohesion of the graph; (ii) they are seeds for the diffusion of habits, methods, ideas and information [26]. Hence, key players may be more efficient in spreading novelties rather than highly central nodes. This paper implements the greedy search algorithm to look for the optimal number of key players and to overcome computational challenges. The algorithm selects an initial set of nodes as seeds. By continuously and iteratively swapping between selected and unselected nodes, the protocol computes if and how much group centrality increases (details in Supplementary Material, chapter 1).

I further investigate the thematic evolution of climate services combining two approaches. content analysis is performed on the set of abstracts and titles included in the database. Content analysis transforms non-numerical material into quantitative information. It is the systematic analysis of textual, visual and audio inputs to identify regularities and patterns in a corpus of matters [27]. The output of this effort consists in the dynamic characterization of top mentioned terms throughout the timeframe. Content analysis also serves as input for co-word analysis. This methodology links science mapping and bibliometrics to grasp connections in textual material [28] and provides a thematic map that spatially allocate topics on a 1:2 plane.

The integration of different disciplines – from scientometrics to content analysis – represents the true originality of this work. This chapter works through a high degree of interdisciplinarity to offer a comprehensive view of the field and the needs of climate services. By including tools from network science to a bibliometric database, the chapter truly assesses the social structure of individual scholars, institutions and countries. Finally, it moves beyond existing metrics of success of a scholar (e.g. h-index, m-index, productivity) and it engages in analyzing both the power (centrality) of each node and the influence this has in driving the information flow.

3. Results

3.1.Bibliometric analysis

The chapter's database includes a corpus of 363 bibliometric records, published between 1974 and 2018 in 187 sources (journals and books) by 1351 authors from 234 institutions in 72 countries. Research articles (54.54 percent), conference proceedings (14.8 percent), reviews (5 percent) and book chapters (5 percent) represent the majority of records. Research on climate services has grown in numbers with an annual growth rate of 14.67 percent, with a sizeable acceleration between 2005 and 2010. The peak (Figure 1.1S) coincides with the World Climate Conference-3 (2009) and launch of the Global Framework for Climate Services (in 2012). In-between, the first International Conference on Climate Services (2011) marked an important milestone: the conference launched the Climate Service Partnership (CSP) to boost development of climate services. Earth and Planetary Sciences (35.3%) and Environmental Sciences (28.9%) are dominating the sample and are also the most time-consistent disciplines across time. Social Sciences (12.6%), Agricultural and Biological Sciences (4.6%) and Engineering (3.1%) follow suit. Economics, Econometrics and Finance (1.0%) are represented starting from 2010. Anglophone authors and institutions dominate the sample. Multi-country collaborations are prevalent: while the authors from United States mostly publish alone, the overall trend is collaborative research across borders (Figure 1.4S). The most productive authors per number of published records are more diverse: 20% have a background in Environmental Sciences, 20% in Social Sciences and the remaining 60% in Physical Sciences. Despite the heterogeneous cohort of actors involved, climatologists, physicists, and numerical modellers are widely recognised as the most central when it comes to climate services.

3.2.The conceptual structure

The science of climate services has roots in climatology and meteorology but as the innovation has become more user-centric oriented, social science disciplines are more represented and the articles pay more attention to clients' knowledge requirements and the value unleashed by climate services. Literature has responded to this trend by exploring the barriers and opportunities from multidisciplinary angles. The historical citation analysis documents this shift: the most cited articles belong to a more recent body of research [29–31] addressing co-design and co-development of national climate services (Figure 4).

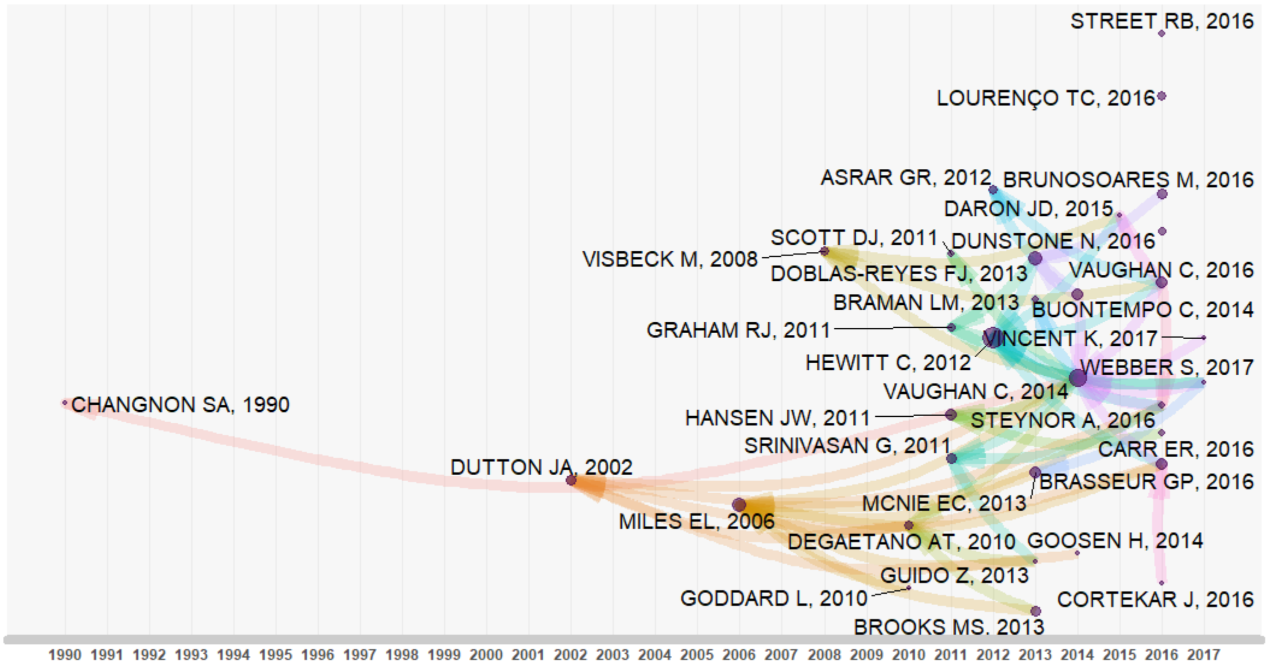


Figure 4 | Historiograph of top cited articles, represented as a directed graph. Nodes' size is equivalent to number of citations; colors are assigned according to citing references. The position along the y-axis is justified only by layout needs.The multidisciplinary character of the top cited records highlights the importance of knowledge exchange across scientific fields. Hewit\t C. (2012) refers to the GFCS: this publication offered direction and guidelines to the research community and provided a global perspective on climate services. It is the most cited record of the sample.

Most frequent keywords (Figure 1.5S) include 'climate change' (365), 'decision making' (236) and 'forecasting' (214) display a fairly steep trajectory since 2001 onwards. Future-oriented keywords dominate, whereas 'observations' or 'reanalysis' are not among the first 100 concepts. 'Seasonal forecasts' gained on popularity, especially in the past eight years. 'Multidisciplinarity' and 'adaptation' have received progressively more attention: the temporal analysis of abstracts shows that 'carbon' and 'emission-related' topics were more popular in early 2010s, while 'user-tailored', 'forecast skills' and sector-specific topics nowadays prevail. 'Adaptation measures' are strongly related to 'risk management' and 'decision making' and require 'climate modelling' and sector-specific studies. Instead, articles related to meteorology and climatology contribute to scientific advancements of the services, but they are still tightly linked to essential climate variables (Figure 7S).

3.3.The social structure

To study the social structure of the field, the bibliographic records are transformed in an undirected graphs (or networks) of co-authorship (N_{ind}), collaborating organizations $\left(N_{aff}\right)$ and countries (N_{co}). This section first describes the N_{ind} structure. The network has a small-world property with tightly interconnected clusters of nodes and most nodes can be reached from any other node through few steps [32] ($SMIndex_{ind} = 7.91 > 3$). The entire co-authorship graph is composed by 1427 nodes (authors) and 7560 edges (co-authorship). The giant component contains 613 nodes and 4326 edges. The network is loosely connected (*density* = 0.024), with fairly distant nodes (diameter = 12). On average, each author is connected through 15.093 links (i.e. *average degree*) to 4.55 scholars (i.e. *average path length*). The probability of two adjacent nodes to be connected (i.e. *clustering coefficient*) is 82.26%. The Principal Component Analysis (PCA) on 42 standardised centrality measures results in five components (Figure 5) that explain 86.1% of the total variance. Buontempo C. happens to be the central agent, directly connecting 21.70% of the nodes and 29.25% edges. He is also connecting some of the most productive scholars according to the bibliometrics results.

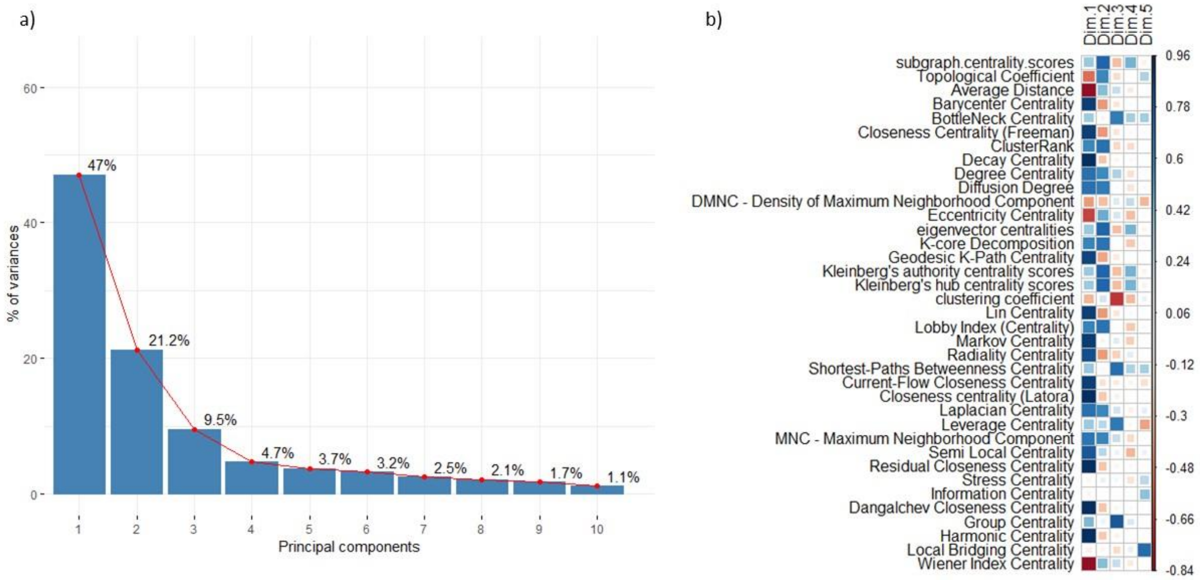


Figure 5| a) Representation of eigenvalues in decreasing order. The percentages represent the portion of variance contained in the data explained by individual components; b) centrality measures included in the PCA are represented according to the degree of correlation with the different dimensions. Dark blue colors are higher correlation.

The community detection protocol produces four different partitions – each per algorithm performed. After modularity maximization check, the Louvain method (Table 1S) leading to 19 communities is preferred.

The network of individuals is represented as a set of complex interactions. Nodes' size is equal to the contribution of each agent to the first five dimensions of the PCA and colors correspond to communities as derived from the Louvain method. The most central authors (Figure 6) are located in five communities, which happen to be the largest in size. Only three (Buontempo C., Hewitt C. and Kumar A.) are listed among the most productive authors (per number of papers produced). Hence, quantity is not an automatic predictor of the "power" of agents, but rather a complementary feature. By looking at topology, two big communities are polarizing the network. The central group (in orange) is deeply connected: authors are linked through a number of publications, one of which contributed to the scientific knowledge around sub-seasonal forecasts [33]. The purple cluster (community 1) embraces authors involved and bounded in a European project ERA-CLIM2, under the Seventh Framework Program [34].

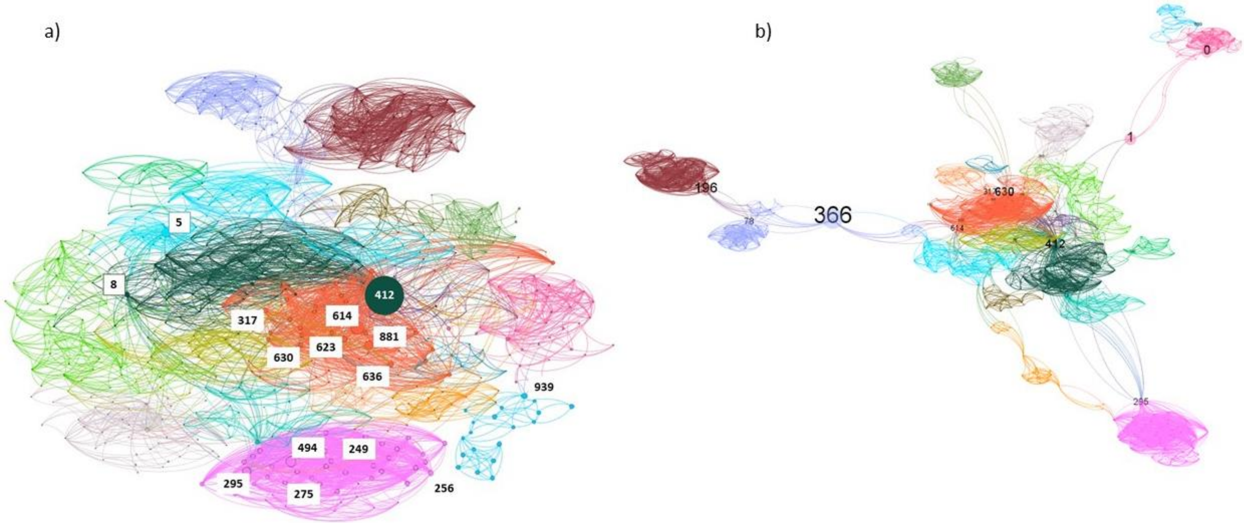


Figure 6 | a) The individual scholars' network. Colors represent communities as deducted by the Louvain method. Node sizes gives the centrality of each author, as derived from the PCA; Buontempo C (412) is the most central, followed by Kumar A. (614), Wintzer J. (494), Hewitt C. (5), Webb RS. (881), Schulz J. (295), Kjellström E. (623), Jack C. (939), Zebiak SE. (636), Brönniman S. (249), Jourdain S. (256), Ray AJ. (317), Brown TJ. (630), Doblas-Reyes F. (8) and Blaschek M. (275). b) The keyplayers represented with their own communities. The top 20 are (ranked in decreasing order): Kolli RK. (366), Baklanov A. (196), Daly M. (1), Vincent K. (0), Brown TJ. (630), Buontempo C. (412)., Grimmond CSB. (78), Jacob D. (6), Schulz J. (295), Kumar A. (614), Ray AJ. (317), Soubeyroux J-M. (425), Jack C. (939), Vaughan C. (341), Vautard R. (702), Hewitt C. (5), Kjellström E. (623), Coughlan De Perez E. (103), Guido Z. (343) and Zebiak SE. (636).

The contribution of each node to maintain the cohesiveness of the graph is measured as suggested by Borgatti (2006). Top influential nodes (key players) do not entirely correspond to the most central ones (Figure 6). Indeed, the set of key players includes some "bridging" scholars: they link different communities co-authoring with well-known and highly recognized authors. The key players are mostly involved in advancing numerical models, predictions and physical sciences, but they are also active in providing inputs about decision-making and user engagement. Hence, they do not just connect distant communities, but they also embody the conceptual framework in which climate services have been developed. They are "brokers" of knowledge generated throughout the network: by working as bridges both in physical and content level, they facilitate the information flow.

The institutional network N_{inst} contains 234 nodes and 1578 edges. The network is more cohesive than the individual one N_{ind} with density equal to 0.057. Nodes are also closer (*diameter = 6*). The average degree is 13.487 and each affiliation is linked to 2.750 (i.e. *average path length*). The average clustering coefficient is very high: 85.80% (higher than N_{ind}). The same methods as for N_{ind} to detect centrality, community structure and degree of influence are followed. Centrality is the contribution of each institution to the first four dimensions, which explain 86.8% of the total variance of the sample. The top institution is Columbia University, with a centrality score of 4.358 (21.79% of the overall network and 28.14% of the overall edges), followed by University of Reading (3.687), University of Oxford (1.476), Desert Research Institute (1.422), University of East Anglia (1.404) and University of Helsinki (1.234). As for N_{ind}, the Louvain method has the highest modularity. The algorithm finds 13 communities: the biggest (community 6) has 31 members, while the smallest (community 1, 3 and 8) have only 7. The geographical location of institutions included in the sample appear in N_{inst} is insightful. African universities are clustered in the same group as the Chinese research institutes. German speaking and Belgian institutions have a tight connection. English-speaking (UK and USA-based) affiliations are cooperating with a heterogeneous set of actors: Columbia University is clustered together with other American institutes, but also co-publishes with the London School of Economics (LSE) and the Swedish Meteorological and Hydrological Institute (SMHI). The University of Reading has, instead, a strong European basin of co-publications, but the community it belongs to also includes the NASA Goddard Institute for Space Studies and Colorado State University. The European institute with strongest connection overseas is Wageningen University.

The set of key players in the network is, as for N_{ind} , different from the most central ones and provides the ground for some insightful considerations. The most influential node happens to the University of Nairobi, which acts as connector of extra-EU countries mainly located in Africa or China, with European and American institutions. Reasons for this may be related to the IGAD Climate Prediction and Applications Centre, where teams of researchers work on short, medium and long-term products and applications. Also, the Joint Research Center acquires importance: its role in bridging knowledge around climate services produced in different areas of the world facilitates the diffusion of information and reduces distances in the network, increasing cohesiveness. Given the widespread collaborations that the UK Met Office has, its influence in spreading ideas, methods and knowledge on climate services increases exponentially if compared with the centrality metrics. Not surprisingly, other well-established research institutions are listed among the top ten influential of the network (the National Center for Atmospheric Research and ECMWF). The top ones are not just providers of climate information services, but they are also producers and purveyors of climate data and information. Furthermore, it seems that interactions are strongly dependent on the level of economic development: African, South American and Asian institutions have tight bonds. Our analysis delivers a polarized picture that is possibly driven by project funding and calls for deeper analysis.

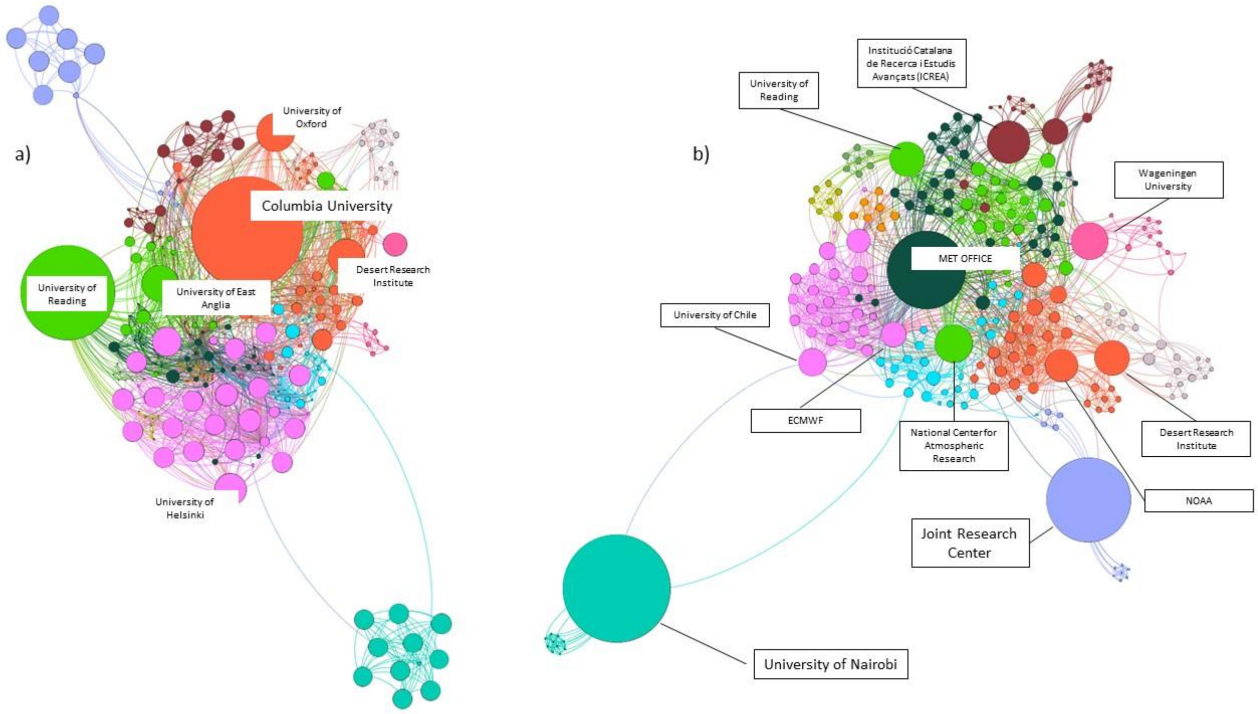


Figure 7 | a) The network of institutions. Colors represent different communities, as derived from the Louvain method and node sizes are equivalent to the outcome of the PCA; b) the institutional network with highlight on the most influential actors. Nodes' size is derived (as in the individual scholars' case) from Borgatti (2006).

4. Conclusions

This chapter maps the research landscape on climate services by analysing a sample of articles published between 1974 and 2018. Results provide a dynamic overview of the most relevant topics explored by the pool of scholars and institutions, as well as the social interactions that shape co-authorship. Scientific production on climate services is higher than expectations: the interest has been stimulated by the launch of multiple European and international initiatives, that contributed closing the gap between science, policy and action. Their action-driven component allowed climate services to progressively shift from mitigation towards adaptation. Hence, they are used as science-based tools capable of supporting decision-making by building on interdisciplinary expertise. The use of Network Analysis further complements these findings. The combination of centrality analysis, community detection and bridging properties made possible the exploration of the mechanisms that facilitate diffusion within the reference networks. These node-specific and graph-level characteristics support the general understanding of how the field of climate services is developing and provides a sophisticated overview of the most influential agents in promoting new ideas, methods and topics.

Our analysis also provides details about bridging agents in the network: these actors are crucial in brokering information and speed the diffusion of information, reducing fragmentation in the network. At author level, the set of key players produce knowledge about physical sciences and decision-making. Hence, they contribute to filling the gap between provider and users with their scientific production. Institution-wise, the higher the geographic and field heterogeneity within a single publication, the stronger the influence within the network. Hence, interdisciplinarity is an asset to promote the reception of ideas, especially when it comes to user needs, value of the information, risk assessment and sector-specific adaptation. Interestingly, those institutes that provide inputs to build fully operational climate services are listed among the most influential (University of Nairobi, Joint Research Center, Met Office).

The chapter offers a novel contribution to the literature on climate services. First, it advances research by integrating bibliometrics, network science and content analysis in a consistent framework. This promotes a comprehensive outlook of the conceptual and social structure of the network of individual and institutional actors publishing in climate services domain. Second, the chapter moves beyond the boundaries of conventional systematic reviews and tackles where strengths and weaknesses of research on climate services lie by looking at structural properties of the field.

Despite the novelty of our approach, limitations exist. In particular, the initial query drives the bibliographic sample. Climate services are not univocally defined, and they have formally received attention since 2011, while some of the documents included were published from 1974 onwards. However, the definition of climate services has always been voluntarily broad: the keywords used to perform the query allow for maximum heterogeneity and are aligned to the flagship initiatives promoted to unleash climate services' potential [35–37]. Furthermore, bibliographic databases – such as Scopus – are biased towards English-based records. However, scientific production adopts English as official language. The sample is populated by peer-reviewed material only, leaving nationally-relevant reports, protocols and regulations out. Also, climate services often include other products and platforms, such as decision-support systems, hydro-meteorological services and even weather services. In this chapter, "climate services" is deemed as the most general and policy-oriented term, capable of capturing the whole period under study, but strongly related to the recent initiatives.

References

1. Cohen, P. J. *et al.* Understanding adaptive capacity and capacity to innovate in social-ecological systems: Applying a gender lens. *Ambio* **45**, 309–321 (2016).
2. Brooks, M. S. Accelerating Innovation in Climate Services: The 3 E's for Climate Service Providers. *Bulletin of the American Meteorological Society* **94**, 807–819 (2013).
3. Directorate-General for Research and Innovation, E. Commission. European roadmap for Climate Services. in (European Commission, 2015).
4. Stigter, K. Policy support for capacity building in weather and climate services focused on agriculture. *Journal of Agrometeorology* **10**, 107–111 (2008).
5. Lechthaler, F. & Vinogradova, A. The climate challenge for agriculture and the value of climate services: Application to coffee-farming in Peru. *European Economic Review* **99**, 5–30 (2017).
6. Li, Y., Giuliani, M. & Castelletti, A. A coupled human-natural system to assess the operational value of weather and climate services for agriculture. *Hydrology and Earth System Sciences* **21**, 4693–4709 (2017).
7. Lindberg, F. *et al.* Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services. *Environmental Modelling and Software* **99**, 70–87 (2018).
8. Jones, L., Champalle, C., Chesterman, S., Cramer, L. & Crane, T. A. Constraining and enabling factors to using long-term climate information in decision-making. *Climate Policy* **17**, 551–572 (2017).
9. Bruno Soares, M., Alexander, M. & Dessai, S. Sectoral use of climate information in Europe: A synoptic overview. *Climate Services* (2017) doi:10.1016/j.cliser.2017.06.001.
10. Goddard, L. *et al.* Providing Seasonal-to-interannual climate information for risk management and decision-making. in *Procedia Environmental Sciences* vol. 1 81–101 (Elsevier B.V., 2010).
11. Scott, D. & Lemieux, C. Weather and climate information for tourism. in *Procedia Environmental Sciences* vol. 1 146–183 (Elsevier B.V., 2010).
12. Scott, D. J., Lemieux, C. J. & Malone, L. Climate services to support sustainable tourism and adaptation to climate change. *Climate Research* **47**, 111–122 (2011).
13. Broadus, R. N. Toward a definition of "bibliometrics." *Scientometrics* **12**, 373–379 (1987).
14. Haunschild, R., Bornmann, L. & Marx, W. Climate Change Research in View of Bibliometrics. *PLOS ONE* **11**, e0160393 (2016).
15. Ma, A., Mondragón, R. J. & Latora, V. Anatomy of funded research in science. *Proceedings of the National Academy of Sciences of the United States of America* **112**, 14760–5 (2015).
16. Youngblood, M. & Lahti, D. A bibliometric analysis of the interdisciplinary field of cultural evolution. *Palgrave Communications* **4**, 120 (2018).
17. Barabasi, A.-L. *Network Science*. (Cambridge University Press, 2016).
18. Baronchelli, A. The emergence of consensus: a primer. *Royal Society of Open Science* **5**, 172189 (2018).
19. Borgatti, S. P., Mehra, A., Brass, D. J. & Labianca, G. Network analysis in the social sciences. *Science* **323**, 892–5 (2009).
20. Castellano, C., Fortunato, S. & Loreto, V. Statistical physics of social dynamics. *Reviews of Modern Physics* **81**, 591–646 (2009).
21. Newman, M. E. J. The Structure and Function of Complex Networks. *Society for Industrial and Applied Mathematics* **45**, 167–256 (2003).
22. Newman, M. E. J. & Girvan, M. Finding and evaluating community structure in networks. *Physical Review E* **69**, 026113 (2004).
23. Barabasi, A.-L. *Network Science*. (Cambridge University Press, 2016).
24. Li, W. & Schuurmans, D. Modular Community Detection in Networks. in *Proceedings of the*

Twenty-Second International Joint Conference on Artificial Intelligence (2011).
25. Granovetter, M. S. The Strength of Weak Ties. *American Journal of Sociology* **78**, 1360–1380 (1973).
26. Borgatti, S. P. Identifying sets of key players in a social network. *Comput Math Organiz Theor* **12**, 21–34 (2006).
27. Krippendorff, Klaus. *Content analysis : an introduction to its methodology*. (2004).
28. Cobo, M. J., López-Herrera, A. G., Herrera-Viedma, E. & Herrera, F. An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field. *Journal of Informetrics* **5**, 146–166 (2011).
29. Hewitt, C., Mason, S. & Walland, D. The Global Framework for Climate Services. *Nature Climate Change* **2**, 831–832 (2012).
30. Vaughan, C. & Dessai, S. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* **5**, 587–603 (2014).
31. Miles, E. L. *et al.* An approach to designing a national climate service. *Proceedings of the National Academy of Sciences of the United States of America* **103**, 19616–19623 (2006).
32. Mehlhorn, H. & Schreiber, F. Small-World Property BT - Encyclopedia of Systems Biology. in (eds. Dubitzky, W., Wolkenhauer, O., Cho, K.-H. & Yokota, H.) 1957–1959 (Springer New York, 2013). doi:10.1007/978-1-4419-9863-7_2.
33. White, C. J. *et al.* Potential applications of subseasonal-to-seasonal (S2S) predictions. *Meteorological Applications* **24**, 315–325 (2017).
34. Buizza, R. *et al.* The EU-FP7 ERA-CLIM2 Project Contribution to Advancing Science and Production of Earth System Climate Reanalyses. *Bulletin of the American Meteorological Society* **99**, 1003–1014 (2018).
35. Barron, E. J. A climate services vision: First steps toward the future. *Board on Atmospheric Sciences and Climate* (2001).
36. World Meteorological Organisation, W. Climate Knowledge for Action: A Global Framework for Climate Services –. (2009).
37. Street, R., Jacob, D., Parry, M., Runge, T. & Scott, J. A European research and innovation Roadmap for Climate Services. *European Commission* (2015).

Finding the right dam(n) partners for a just energy transition[4]

1. Introduction

Supporting the transition towards a carbon neutral global economy requires the conversion of our energy systems to fully renewable sources [1,2]. To work, this transformation calls for the mobilization of required financial capital, beside technological and knowledge transfers [3,4]. Over the past decades, solar and wind technologies have witnessed growth in investment and capacity[5] and their role is expected to increase in the future[1]. However, hydropower remains the primary renewable energy technology by capacity and generation[5] accounting for approximately 60% of international investment flows in renewable energy [6]. In particular, hydropower is at the core of several developing countries' energy systems[5,7], where it provides the base for energy security and makes progress towards the UN Sustainable Development Goals 13 (climate action)[8] and 7 (energy)[9]. As such, hydropower helps to fill the "transition gap": it supplies low-cost clean electricity and continuous power with existing infrastructure while countries integrate other emerging and clean technologies into their energy systems[9].

Despite its importance in the overall energy mix, capacity additions and investments in hydropower have been showing a decreasing trend for the last five consecutive years (2019 global net additions declined 45% with respect to 2018 [5]. The need for significant capital investment, along with the controversial socio-economic and environmental impacts of hydropower facilities[10], constrain project development[11]. Indeed, financing hydropower projects requires investors to pay large upfront capital and lock-in their capital for decades (hydro projects can last for 100 years), while also bearing high investment risks[12]. A large hydropower dam on average costs more than a billion dollars [11], carries relevant construction/development risks, domestic risks associated with emerging economies (macroeconomic conditions, business confidence, policy uncertainties and regulatory frameworks), and has a long-term repayment period [12]. These factors imply that financial actors must be assembled to ensure access to finance for hydropower projects and have patient capital to stay through the natural cycle of the investment.

[4] This chapter is derived from Larosa, F., Rickman, J. and Ameli, N., submitted for consideration to a peer-review journal of IF 10.87

Beyond financial aspects, different hydropower co-investment arrangements are relevant to ensure that benefits reach multiple groups, achieving energy justice[7,13]. The study of the complex landscape of investors in renewable energy technologies caught the attention of scholars interested in the direction of financial flows at global level[14,15]. These findings offer insights on global inequalities in access of financial resources, but fail at questioning the investment models and financing structures have been and are enabling the energy transition. Much of current literature also lacks a technology-specific financial outlook [16] and tends to assess the importance of different actors by using aggregated international financial flows as a key metric [14]. Other scholars produced evidence on investment trends in selected niches of hydropower financing[13]. Despite the importance of their contribution, case-based and comparative studies call for complementary quantitative insights.

A parallel stream of literature studies the landscape of investors in renewable energy technologies by looking at their public-private nature[17–21] . These works look at market and policy mechanisms that trigger a crowd-in effect of financial resources and assess whether the public sector facilitates incumbent private players in diverse markets. The interplay between public and private financial sources is an important risk-mitigation factor and allows international finance to flow from developed to emerging nations[20,22]: public actors employ patient capital that bares initial investment risks, paving the road for the private sector to step in[23]. The public-private investment models are appealing for high-risk and low track investment record countries, where pioneering financial institutions are most needed[24,25]. However, they raise questions about over-indebtment of poor countries[26,27], especially in the hydropower case where cost overruns are highly concerning[28,29].

My work explores which investment models and co-investment patterns enabled hydropower deployment over the past century (1903-2020). First, I detect how different actors co-mobilised the capital needed for hydropower projects at global level. Second, I zoom into the most critical investors who hold the project finance landscape together, allowing critical connections within and across different geographical areas, especially towards the most vulnerable countries. Finally, I rank investors on their ability to form public-private partnerships over time that stimulate joint investments and facilitate risk-mitigation practices.

Results show that public and international institutions are the critical actors driving hydro finance through multilateral and bilateral financing mechanisms and global PPPs. These investors interact both within and across distant communities (meant as clusters of highly connected investors) acting as connectors and allowing finance to reach the most vulnerable areas. They integrate climate objectives into their development goals by mandate, enhancing economic prosperity and sustainable growth, while also boosting clean and affordable energy sources. This virtuous investment cycle is enabled by the diversity of partnerships activated by international institutions, who pave the road for banks and private actors across multiple countries.

This chapter contributes to the literature in two ways. First, it analyses the hydropower-specific global investment landscape, providing a macro picture of the critical actors and co-investment dynamics that took place over the past century. Financial capital committed in the past provides a clear indication of countries' trajectories. In the present and near future. Given hydropower dams require time to build and repay, investments in this technology signal the transition pathways of different areas of the world. Second, the chapter introduces a novel metric that measures the ability of actors to form public-private partnerships. The index signals actors that built a strong track records in blended investment models in the past and opens new research questions for the future.

As one of the biggest challenges in sustainable energy transitions is likely to be in developing countries, the effort in this chapter serves as monitoring tool. The analysis is a starting point to assess the speed of the energy transition at country level and to detect whether optimal investment models exist to accelerate the capital deployment in the most vulnerable areas of the world. A strong investment architecture and effective investment channels will accelerate sustainable power deployment while leaving room for new technologies in the energy transition.

2. Materials and methods

The analysis is based on small and large hydro investments over the past century (1903-2020) (Bloomberg New Energy Finance dataset), which combines information about project finance, the economic actors involved and the related transactions. In particular, key project information includes its value, capacity, and location, financing structure used, and actors involved (e.g. current owner, project developer). In addition, details of companies and organisations involved in developing and financing hydropower projects, such as their country and business description, as well as transaction-specific data, such as the type of finance: debt and equity.

I focus the analysis on completed small and large hydropower projects. I merge the project, transactions, and organisations database to obtain a complete overview of hydropower project financing at global level. After merging and cleaning, I obtain a dataset of 3610 observations, where each record represents a financial transaction referring to a specific project as described by a unique

ID. I assign categories (Table 1) to each investor to reflect their nature and business, through a combination of automated and manual routines based on Bloomberg's categorization data (e.g. "Public" and "Private"). I filled the missing company-reported information by analysing the companies' abstract reported in the Bloomberg database and through a manual search.

Table 1 | Investor categories

Type	Ownership	Sub-activity	Description
Non-financial types	Private	*Renewable Energy Company*	Core focus on renewables. Typically, component manufacturers, project developers, O&M services in RE
		Energy Company	Core focus on traditional energy sources. Can have renewables in portfolio, but they are highly involved in conventional energy. Typically, component manufacturers, project developers, O&M services in conventional energy
		Private Utility	Main business is the generation and distribution of energy. They are not state-owned, nor public. Generation and distribution are two necessary conditions
		Diversified	All remaining private non-financial companies, including engineering and construction companies whose main business is not in the energy sector
	Public	Public Utility	Main business is the generation and distribution of energy. Owned by largest share by public actors
		Government Agency	Government ministries, authorities, municipalities, councils, research institutions, universities
		State-owned Institution	All remaining state-owned non-financial companies e.g. oil and gas exploration companies. These institutions are both private and public
Financial types	Private	*Commercial Bank*	Main business is commercial banking
		Institutional Investor	Non-bank financial companies e.g. private equity firms, pension funds, investment funds, insurance companies
		Non-profit investor	Foundations, co-operatives, community organisations
	Public	*Public Bank*	State-owned commercial banks, national development banks, export credit agencies
		International and multilateral actors	Multilateral development banks and funds, organisations and institutions

I represent the hydropower project financing landscape as a set of interactions (links) between investors (nodes) (Figure 8). At the micro level, investors raise (equity) and borrow (debt) capital to finance projects [36] depending on their heterogeneous preferences, market expectations and risk appetite [16,37–39]. Nodes belong to two disjoint and independent sets and they are linked through a direct connection from equity (Q) to debt (B). Hence, links between nodes materialise in the presence of at least one loan or bond between an equity and debt investor. Links are all equal (i.e. the network is unweighted) and they form a complex network of interactions, organized in structures, namely communities. Communities are groups of investors more densely connected than the rest of the system [40]. Communities also simplify the study of the system by acting as meta-levels and highlighting properties that would otherwise have been neglected [40].

Communities are identified by clustering links between nodes to assess whether investors belong to overlapping communities, a commonly observed feature in real world networks [41,42]. I extract link communities from the empirical network by mirroring existing literature [43,44]. I measure the similarity between pairs of links $e_{ik} and\ e_{jk}$ sharing at least a node k. Similarity is obtained from the Jaccard coefficient, which measures the asymmetries between two variables (see Supplementary material for details). Pairwise similarities are the seeds of a hierarchical dendrogram where branches describe communities. Communities are formed by links occupying a unique position and nodes assigned to multiple clusters. This setup responds to an economic intuition: investors may potentially belong to multiple groups (regions, countries, legal status, mandate). On the contrary, links between them exist for a particular purpose (de-risking investments, forming a new partnership). Hence, connections are unique, while investors populate different clusters.

BNEF hydropower asset transaction data

Project Name	Date	Debt Investors	Equity investors
Hydropower A	DD/MM/YYYY	Bank A, Bank B	Company A
Hydropower B	DD/MM/YYYY	Bank A, Bank C	Company B
Hydropower C	DD/MM/YYYY		Company B

Bipartite network representation

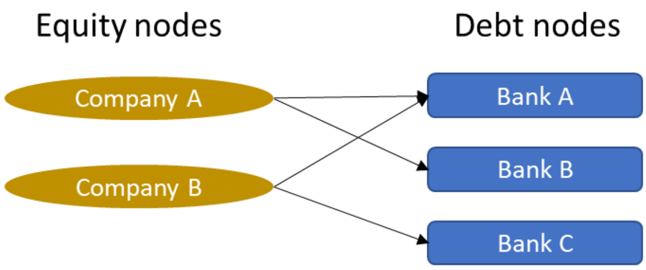


Figure 8 | Representation of bipartite network structure derived from BNEF asset transaction data

To further understand the financing structure behind hydropower investments, I compute a community-based centrality score (CC). The CC is strongly anchored to the link community structure. In fact, well-connected investors are not just the ones with many active co-investments, but rather those who operate in communities with high connecting power. Investors with high CC score will belong to communities capable of reaching distant groups of actors, hence spreading the available financial resources to different players. I express CC (equation a) as the weighted sum of communities a node belongs to over the X communities weighted by the average similarity between pairs of communities:

$$C_C(i) = \sum_{i \in j}^{X} \left(1 - \frac{1}{m} \sum_{i \in j \cap k}^{m} S(j,k)\right) \qquad \text{(a)}$$

where the communities X to which node i belongs to are summed together; $S(j,k)$ is the similarity between community j *and* k defined as the Jaccard coefficient for the shared nodes between each pair of communities. The summation is averaged over m communities paired with community j where node i also belongs.

Finally, I measure the ability of each investor to form public-private partnerships (PPPs). Public-private partnerships (PPPs) are becoming an increasingly popular investment model to bridge different expertise and knowledge gaps [36,45]. Investors act as brokers of information: the more diverse their network, the lower their risk on investing in low-return projects [45]. PPPs also support coordinated objectives by crowding in private finance to maximize the provision of capital. In the climate finance domain, being connected to diverse stakeholders helps de-risk projects, ensures the sustainability of long-term commitments [46,47] and triggers virtuous learning mechanisms via co-investments [48].

I introduce a novel metric, the Partnership Index (PI), to assess the strength of each investor in forming connections with diverse stakeholders (equation b). The PI acknowledges the role of network structure in influencing the resource transfer process (see details in Supplementary material). The metric builds upon the intuition described in social networks literature [49] and applied by (Reagans & McEvily, 2003), where investors connected to multiple groups access a wider pool of information and do not process redundant knowledge. The PI is an investor-specific measure of diversity: the wider the set of connections with different actors, the higher the index. Given the capital and time-intensive nature of hydropower projects, diverse co-investments allow each player to solve multiple challenges.

The PI is computed for the whole time series and across different time splits. Hence, I check whether investors opened market opportunities to incumbents overtime, leading to a crowding-in effect and pooling together private and public finance.

$$p_{ik} = \sum_{j}^{N_k} z_{ij} \Big/ \sum_{q}^{N} z_{iq} \qquad \text{(b)}$$

This metric is the ratio of two sums. The numerator counts investor i's connections with N_k distinct categories of investor, where z_{ij} = 1 if the connection to category j exists and 0 otherwise. The denominator counts the N connections of node i with all other investors q. The ratio describes the extent to which the connections of node i are spread between different categories of investor.

3. Results

3.1. How investors group together and why it matters

The dataset well represents the distribution of hydropower facilities at global levels. It is widely dominated by smaller projects (in value) especially prior to 2000s (Figure 9). Small hydropower projects range between 0.070 to 674 MW and include Run of River, Existing Dam and New Dam projects. We observe a substantial interest in East Asia and the Pacific and a growing wide investment trends in Latina America and the Caribbean (with Brazil as a hydropower champion).

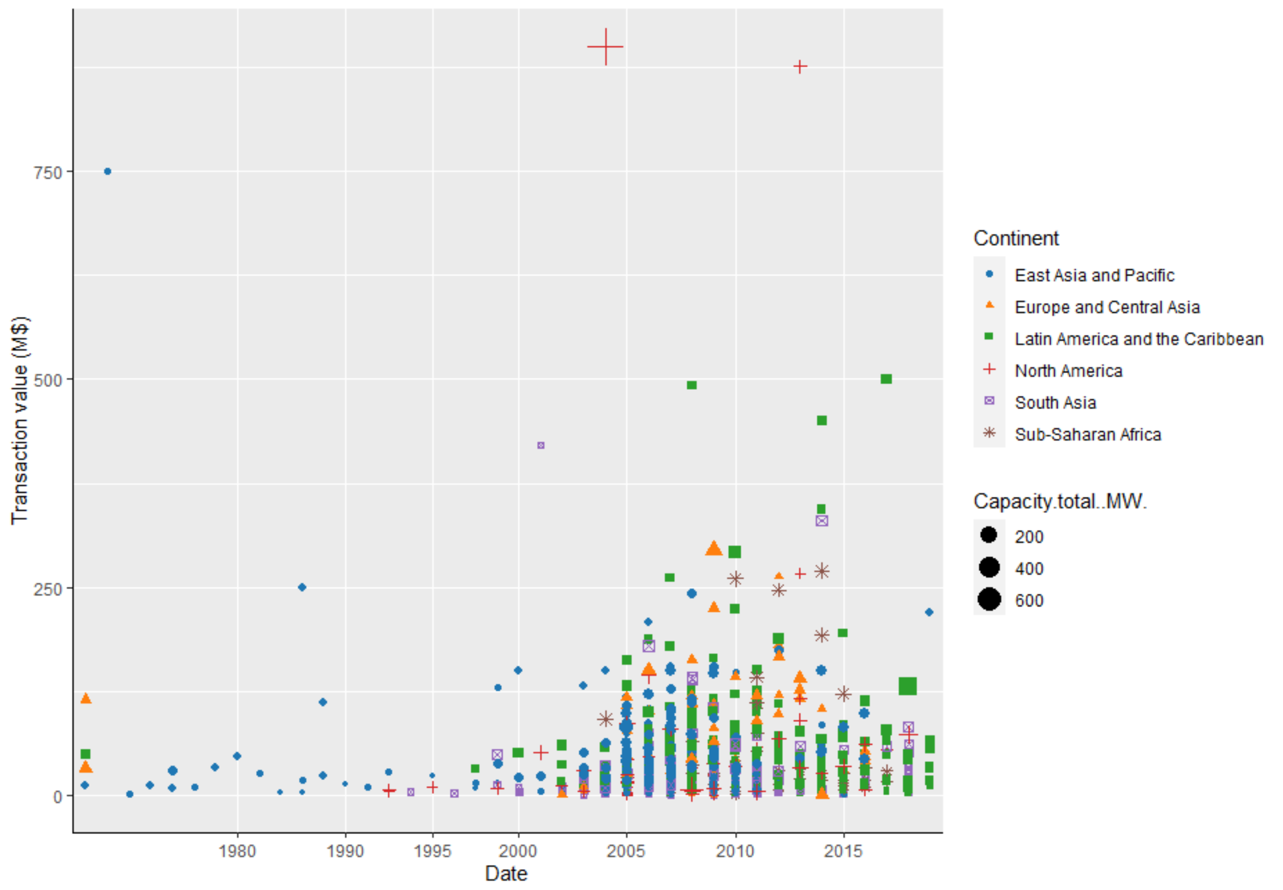


Figure 9 | Distribution of hydropower facilities per continent, capacity and transaction value

Renewable energy firms are the dominant players of the equity market (Figure 2a, Supplementary material), followed by private utilities. This is striking in the top three countries (per transaction value): Brazil, China and United States. The market structure differs in Japan, where private utilities take the largest share. Public banks and commercial banks shape the debt market (Figure 2b, Supplementary material). Different countries have distinct market structures: while some are oriented towards a more publicly-owned form of debt (Brazil and Costa Rica), others are stimulated by loans and bonds provided by commercial banks (i.e. Turkey and Spain).

The chapter moves to the study of the characteristics of the network of hydropower finance investments to detect possible regularities and important features of the global landscape. I find a strong presence of hubs in the debt network. Hubs are nodes with a number of links that greatly exceeds the average. The topological analysis reveals the existence of a community structure. Hubs act as connectors of often distant groups of investors. There are 95 overlapping communities (groups of related investors [50]), where different players connect for a common goal (e.g. forming a new partnership) rather than reflecting their specific characteristics (business nature or mandate).

The investor community analysis reveals geographical investment patterns. In far-east Asian countries (Korea and Vietnam) the interactions between domestic investors (i.e. community density) are more frequent compared to the rest of the world. In India, the financial landscape is dominated by domestic state-owned banks, while Japan has a strong presence over the continent through the investment made by its second biggest bank, namely Sumitomo Mitsui Banking Corporation and a private utility (Kansai Electric Power Co Inc.). Brazil has a similar investment architecture, where investors act through the BNES, which facilitates transactions in both large and small hydropower projects. Investors mainly cluster together at national and regional level confirming the existence of a "home bias" in investments [51].

Multilateral, bilateral and blended finance agreements constitute a powerful exception to home-bias (Figure 10) and they reveal important insights about different contract structures in the hydropower financing. Multilateral development banks provide mainly multilateral finance to host countries directly. While bilateral finance includes primarily loans and debt reliefs to finance large hydropower projects in low-income African (Angola, Cameroon, Uganda and Zambia) and Asian middle-income countries (Indonesia and Thailand) by far-East actors (China, Korea and Japan), as well as in selected East European countries (Armenia and Georgia). Finally, blended finance agreements include bilateral finance institutions, governmental budget and private companies. These contracts are usually complex in their nature as they often rely on a set of mixed actors and subsidiaries of the national governments. They increase beneficiaries' public debt and they have a strong uptake in the African continent (Mali, Burundi, Senegal and Uganda) and in low-income Asian countries (i.e. Pakistan). We observe a strong presence of foreign investors in lower-income countries. These players are not limited to the pool of international institutions and organisations, but they also include private utilities, commercial banks and renewable energy firms.

Multilateral and bilateral institutions are also highly ranked by CC values: 40% of the highest 20 ranked investors by centrality score are international actors and multilateral organisations. I find that by connecting investors in distant geographies, they boost hydropower deployment globally and embody the globalized nature of the financial system. Moreover, highly central actors are involved in at least one large (> 50 MW) hydropower project, where the highest capital disbursement is concentrated.

The International Finance Corporation (IFC) ranks first in terms of CC and connects several overlapping communities (including South America and Africa). It enables co-investments between governmental agencies (e.g. Uganda Development Corporation), renewable energy firms (e.g. Nachtigal Hydro Power Co), international development agencies (e.g. Aga Khan Fund for Economic Development) and institutional investors (e.g. CDCD Group). Highly ranked investors also affect other investors' centrality, revealing a strong network effect. For instance, the second ranked investor is Nachtigal Hydro Power Company (NHPC), a private company jointly owned by Electricité de France (EDF, 40%), International Finance Corporation (IFC, 30%) and the Republic of Cameroon (30%). NHPC shares with the IFC the interests in the African continent and operates with other international organisations (i.e. European Bank for Reconstruction and Development, African Development Bank, OPEC Fund for International Development) in other continents.

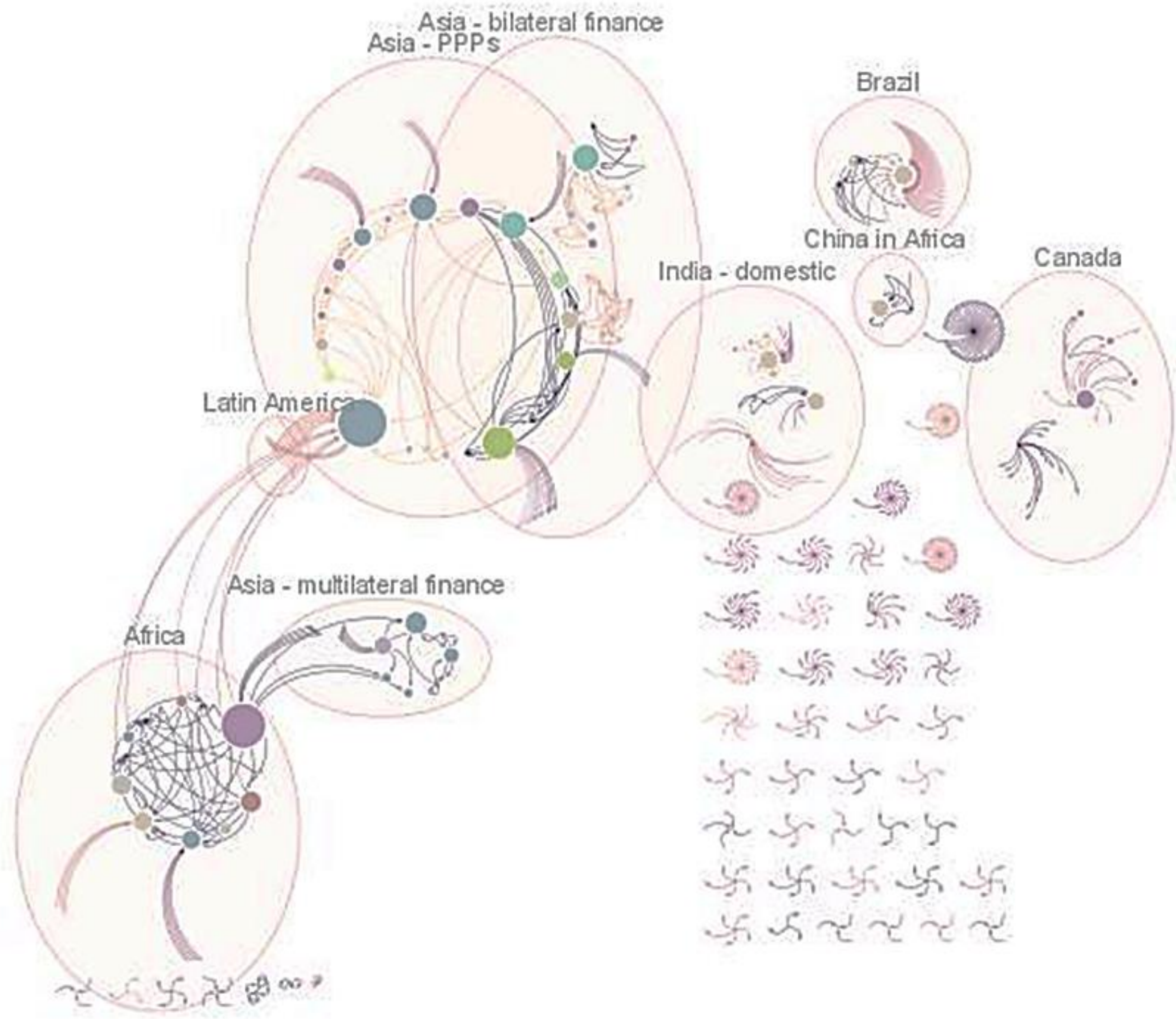


Figure 10 | The landscape of project finance for hydropower projects. Investors are represented as bubbles where colours identify their legal status and their size express the community-based centrality score.

The community findings highlight the challenge of mobilizing funds for developing countries. Since most finance is sourced domestically and mature capital markets are mainly in developed countries, the most central group of investors (e.g. multilateral and bilateral institutions) play a key role in redirecting financial flows across borders. The mismatch between geographical location of investment needs and available capital, also implies the need to find novel mechanisms to attract and crowd-in private finance especially in developing countries, underlining the complexity behind project finance for the energy transition.

3.2.Partnerships as crucial leverage to ensure access to finance globally

Many of the most central investors facilitate connections between financial actors operating under a diverse governance (national, regional and international) and legal (public and private) structure. These relationships help to raise public and private funds for strategic objectives (e.g. climate and development), while attracting new stakeholders in the form of partnerships.

Multilateral and bilateral institutions, alongside commercial banks are the top investors per PI (Table 2). Multilateral and bilateral institutions, as well as development agencies, typically form consortia to provide debt financing to renewable energy companies or governmental agencies of the host country. Commercial banks interact with other banking entities and form partnerships with multilateral institutions. Commercial banks trigger a project financing structure that enables large hydropower projects across the world. The top ten investors by PI promoted projects located mainly in developing and emerging countries (e.g Uganda, Peru, China, India and Vietnam) (Figure 11). This signals their role in enabling capital to flow: by reaching the most vulnerable and triggering investments where financial infrastructures are more fragile.

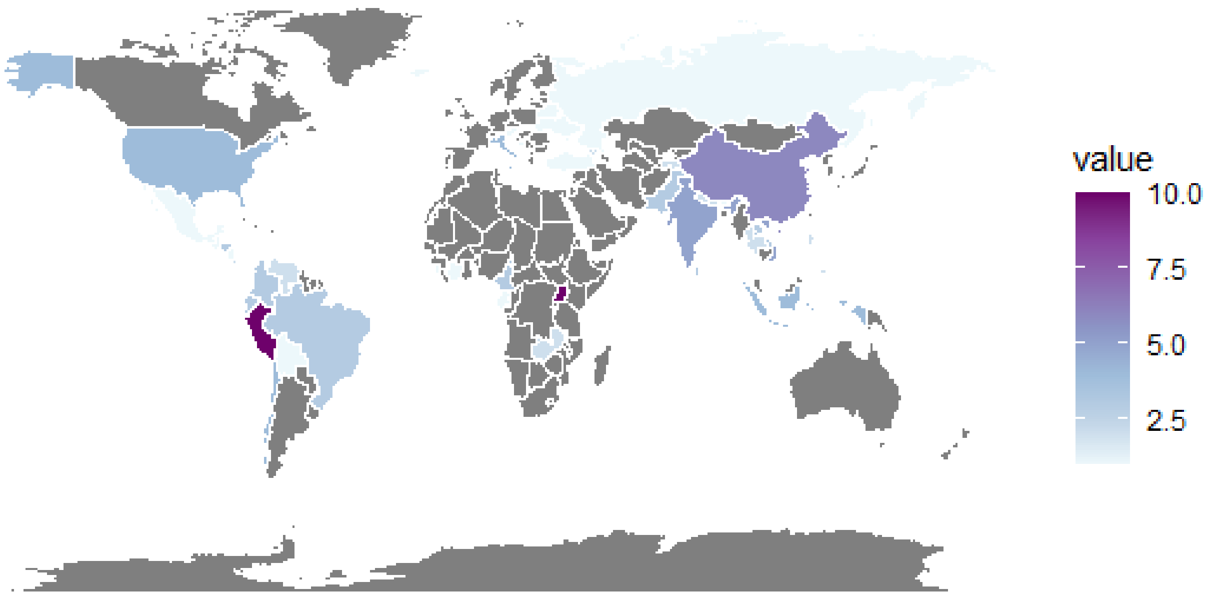


Figure 11 | The location of investments: colors indicate the frequency of partnerships in a given country as activated by the top ten actors

The role of actors in activating partnerships has evolved overtime. Prior to the 1970s and up to the 1980s, multilateral banks (e.g. The Asian Development Bank, the IFC, the World Bank Group) played a central role in enabling partnerships across the world. The hydropower project financing infrastructure changed over the 1990s especially in developing countries, with the entrance of private utilities, renewable energy firms and commercial banks as key facilitators of PPPs in Africa and far-east Asia. In the first decade of the new century, there is a renewed interest of multilateral and bilateral institutions, including European players (e.g. European Bank for Reconstruction and Development, European Investment Bank), which is consistent with the need to support developing countries in both "management and development" [52] of their resources. The 2010s presents a mixed public-private project financing infrastructure. Largely, multilateral and bilateral institutions enabled business opportunities for incumbent and smaller players, widening the diversity of active investors in hydropower project financing.

The analysis shows the relevance of different investors in activating and promoting PPPs for hydropower projects as important mechanisms to access finance globally – they indeed leveraged private capital, especially in the areas with most need. The effectiveness of PPPs is strictly linked to the underlying project financing structures and seems essential to ensure a just transition where climate objectives go together with other SDGs.

Table 2 | The top ten investors by partnership index across the whole timeframe.

Investor	Centrality	Partnership Index ↓	Category
African Development Bank	1	0.875	International and multilateral actors
European Investment Bank	2.9	0.852	International and multilateral actors
Nederlandse Financierings-Maatschappij voor Ontwikkelingslanden NV	2.8947	0.837	Public Bank
International Finance Corp	5.5651	0.835	International and multilateral actors
BNP Paribas SA	3.5714	0.833	Commercial bank
Sumitomo Mitsui Banking Corp	3.6349	0.83	Commercial bank
Inter-American Development Bank	1	0.82	International and multilateral actors
Asian Development Bank	3.6071	0.817	International and multilateral actors
Societe de Promotion et de Participation pour la Cooperation Economique SA	1	0.815	Public Bank
Export Import Bank of Thailand	2.8889	0.815	Public Bank

4. Discussion and conclusions

The Paris Agreement recognises the need to align finance consistently with "climate-resilient development" [53]. The wake-up call is coherent with other existing frameworks (e.g. the Addis Ababa Action Agenda [54] and the 2030 Agenda for Sustainable Development [55]), but it is still far from being sufficient. Maximising the uptake, spread and efficiency of renewable technologies is a key challenge, especially in the most vulnerable areas of the world. Finance supports the shift: enhancing a sustainable and just transition strongly depends on a more equitable access to finance. This analysis moves the attention towards which investment channels and actors enabled the deployment of hydropower across the globe over the past century. The approach of this chapter identifies the critical connections that helped financial resources flow. This is essential for hydropower resources given that the technology suffers from declining investment trends[5] despite its role in supporting several developing economies.

This work offers insights about the systemic complexity of hydropower project financing models. It highlights how investors cluster together and identifies the key actors in connecting public and private efforts to reach the most vulnerable. As finance is dominated by strong home bias, investments in such areas still depend on effective public-private partnerships [56,57] that cross borders and connect diverse stakeholders. Partnerships are also crucial in promoting learning through co-investments and in supporting systemic transformations [48]. I find that international actors, multilateral development banks and bilateral institutions have been critical in widening the market for incumbents, crowding-in different active investors in hydropower project financing. These findings reinforce the need for a global coordination and policy agenda [58,59], but also highlights the importance of the commercial banking sector in boosting a more equal deployment of financial resources.

Strong partnerships have also allowed countries to make progress towards their NDCs, especially where hydropower played a central role in the energy system. For instance, in its updated NDC, Vietnam identified the maximization of hydropower production as a key priority, in line with improved mobilization of capital "for investments in developing the power sector" [60]. India also presented hydropower as an essential energy source in its NDC [61], which is consistent with its pressing domestic energy security objectives. As highlighted by the NDC Partnership Forum [62], solid partnerships are critical to boost a sustainable economic recovery after the COVID-19 pandemic to meet the objectives declared in the single NDCs while restructuring economic prosperity after the shock.

The findings open new research questions. Partnerships could be also powerful tools to align the energy transition objectives with debt sustainability. If successful in building mature markets, partnerships can promote a sustainable domestic environment for investments, reducing the occurrence of debt instruments. Indeed, while creating a space for a tighter climate-development nexus, the strong dependency of developing countries on public resources can increase the pressure on public debt. International, bilateral and multilateral actors are increasingly deploying finance through non-concessional resources [63], which ultimately contributes to higher levels of indebtedness among many developing countries. Understanding the consequences of term and development loans and which financing mechanisms ensure debt sustainability, has to become part of the energy transition agenda [64].

The approach of this chapter does not account for context-specific socio-economic factors that may encourage the formation of public-private partnerships of the establishment of operations in a given area. Variables such as ease of doing business, legislative requirements, fiscal incentives, natural resource endowment would potentially benefit a more in-depth and quantitative assessment of the why partnerships form. The scope of this chapter is restricted to the observation of different co-investment dynamics and the quantification of diverse economic agents' importance. Future research can benefit from the newly computed partnership index and may use it for new research questions.

Finally, future assessments of equitable project finance for hydropower will need to account for changing climate conditions. Past, present and future projects require updated projections of water availability to estimate the return on investments under different conditions [65] hence altering the profitability of different investment models. The use of systemic approaches can incorporate these questions in the policy agenda and fill the existing transition gap that threatens the success of a just transition.

References

1. McCollum, D. L. *et al.* Energy investment needs for fulfilling the Paris Agreement and achieving the Sustainable Development Goals. *Nature Energy* **3**, 589–599 (2018).
2. Bogdanov, D. *et al.* Radical transformation pathway towards sustainable electricity via evolutionary steps. *Nature Communications* **10**, 1077 (2019).
3. Van de Putte, A., Campbell-Holt, A. & Littlejohn, G. Financing the sustainable energy transition. in *The Geopolitics of the Global Energy Transition. Lecture Notes in Energy* (eds. Hafner, M. & Tagliapietra, S.) vol. 73 257–277 (Springer, 2020).
4. IRENA. *Global energy transformation: A roadmap to 2050*. (2019).
5. (IEA), I. E. A. *IEA Tracking Report 2020*. (2020).
6. Renewable Energy Agency, I. *Renewable Energy Statistics 2020*. (2020).
7. Llamosas, C. & Sovacool, B. K. Transboundary hydropower in contested contexts: Energy security, capabilities, and justice in comparative perspective. *Energy Strategy Reviews* **37**, 100698 (2021).
8. Berga, L. The Role of Hydropower in Climate Change Mitigation and Adaptation: A Review. *Engineering* **2**, 313–318 (2016).
9. Oyewo, A. S., Aghahosseini, A., Ram, M. & Breyer, C. Transition towards decarbonised power systems and its socio-economic impacts in West Africa. *Renewable Energy* **154**, 1092–1112 (2020).
10. Sovacool, B. K. & Walter, G. Internationalizing the political economy of hydroelectricity: security, development and sustainability in hydropower states. *Review of International Political Economy* **26**, 49–79 (2019).
11. Ansar, A., Flyvbjerg, B., Budzier, A. & Lunn, D. Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy* **69**, 43–56 (2014).
12. Markkanen, S., Plummer Braeckman, J. & Souvannaseng, P. *Mapping the evolving complexity of large hydropower project finance in low and lower-middle income countries*. *FutureDAMS Working Paper* vol. 2 (2020).
13. Llamosas, C. & Sovacool, B. K. The future of hydropower? A systematic review of the drivers, benefits and governance dynamics of transboundary dams. *Renewable and Sustainable Energy Reviews* **137**, 110495 (2021).
14. Naran, B., Furio, V., Buchner, B. & Linstaedt, J. *Global Landscape of Renewable Energy Finance 2020*. (2020).
15. Buchner, B. *et al. Global Landscape of Climate Finance 2019*. (2019).
16. Mazzucato, M. & Semieniuk, G. Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change* **127**, 8–22 (2018).
17. Rodríguez, M. C., Haščič, I., Johnstone, N., Silva, J. & Ferey, A. Inducing private finance for renewable energy projects: Evidence from micro-data. (2014).
18. Haščič, I., Rodríguez, M. C., Jachnik, R., Silva, J. & Johnstone, N. Public interventions and private climate finance flows: empirical evidence from renewable energy financing. (2015).
19. Polzin, F., Migendt, M., Täube, F. A. & von Flotow, P. Public policy influence on renewable energy investments—A panel data study across OECD countries. *Energy Policy* **80**, 98–111 (2015).
20. Corrocher, N. & Cappa, E. The Role of public interventions in inducing private climate finance: An empirical analysis of the solar energy sector. *Energy Policy* **147**, 111787 (2020).
21. Deleidi, M., Mazzucato, M. & Semieniuk, G. Neither crowding in nor out: Public direct investment mobilising private investment into renewable electricity projects. *Energy Policy* **140**, 111195 (2020).
22. Kapoor, S. & Oksens, L. *Funding the Green New Deal: Building a Green Financial System*. (2011).

23. Mazzucato, M. & Semieniuk, G. Financing renewable energy: Who is financing what and why it matters. *Technological Forecasting and Social Change* **127**, 8–22 (2018).
24. Finance in Common. *Joint Declaration of all public development banks in the world*. https://financeincommon.org/sites/default/files/2021-01/FiCS - Joint declaration of all Public Development Banks_0.pdf (2020).
25. Geddes, A., Schmidt, T. S. & Ste, B. The multiple roles of state investment banks in low-carbon energy finance: An analysis of Australia, the UK and Germany. *Energy Policy* **115**, 158–170 (2018).
26. The World Bank. *International Debt Statistics 2021*. (2021).
27. Carty, T., Kowalzig, J. & Zagema, B. *Climate Finance Shadow Report 2020: Assessing progress towards the $100 billion commitment*. (2020).
28. Sovacool, B. K., Gilbert, A. & Nugent, D. An international comparative assessment of construction cost overruns for electricity infrastructure. *Energy Research & Social Science* **3**, 152–160 (2014).
29. Ansar, A., Flyvbjerg, B., Budzier, A. & Lunn, D. Should we build more large dams? The actual costs of hydropower megaproject development. *Energy Policy* **69**, 43–56 (2014).
30. Polzin, F., Egli, F., Steffen, B. & Schmidt, T. S. How do policies mobilize private finance for renewable energy?—A systematic review with an investor perspective. *Applied Energy* **236**, 1249–1268 (2019).
31. Zhang, F. Leaders and followers in finance mobilization for renewable energy in Germany and China. *Environmental Innovation and Societal Transitions* **37**, 203–224 (2020).
32. Hong, H., Karolyi, G. A. & Scheinkman, J. A. Climate Finance. *Review of Financial Studies* **33**, (2020).
33. Nelson, D. & Pierpont, B. *The Challenge of Institutional Investment in Renewable Energy*. (2013).
34. UNEP. *Financial Institutions taking actions on climate change*. (2016).
35. Kumar, N. *National Development Banks and Sustainable Infrastructure in South Asia*. (2015).
36. Head, C. *The Financing of Water Infrastructure A Review of Case Studies*. (2006).
37. Kaminker, C., Eklin, K., Kawanishi, O. & Youngman, R. *Mapping Channels to Mobilise Institutional Investment in Sustainable Energy*. *OECD Publishing* (OECD Publishing, 2015). doi:10.1787/9789264224582-en.
38. Bergek, A., Mignon, I. & Sundberg, G. Who invests in renewable electricity production? Empirical evidence and suggestions for further research. *Energy Policy* **56**, 568–581 (2013).
39. Barazza, E. & Strachan, N. The impact of heterogeneous market players with bounded-rationality on the electricity sector low-carbon transition. *Energy Policy* **138**, 111274 (2020).
40. Newman, M. E. J. Finding community structure in networks using the eigenvectors of matrices. *Physical Review E - Statistical, Nonlinear, and Soft Matter Physics* **74**, (2006).
41. Palla, G., Derényi, I., Farkas, I. & Vicsek, T. Uncovering the overlapping community structure of complex networks in nature and society. *Nature* **435**, 814–818 (2005).
42. Palla, G., Barabási, A. L. & Vicsek, T. Quantifying social group evolution. *Nature* **446**, 664–667 (2007).
43. Ahn, Y.-Y., Bagrow, J. P. & Lehmann, S. Link communities reveal multiscale complexity in networks. *Nature* **466**, (2010).
44. Kalinka, A. T. & Tomancak, P. linkcomm: An R package for the generation, visualization, and analysis of link communities in networks of arbitrary size and type. *Bioinformatics* **27**, 2011–2012 (2011).
45. Reagans, R. & McEvily, B. Network Structure and Knowledge Transfer: The Effects of Cohesion and Range. *Administrative Science Quarterly* **48**, (2003).
46. Bayliss, K. *et al. The use of development funds for de-risking private investment: how effective is it in delivering development results?* (2020) doi:10.2861/09434.

47. UNDP. De-risking mechanisms can increase private capital to achieve the SDGs. https://www.europe.undp.org/content/geneva/en/home/our-perspective/2017/10/10/De-risking-mechanisms-can-increase-private-capital-to-achieve-the-SDGs-.html (2020).
48. Geddes, A. & Schmidt, T. S. Integrating finance into the multi-level perspective: Technology niche-finance regime interactions and financial policy interventions. *Research Policy* **49**, 103985 (2020).
49. Burt, R. S. Range. in *Applied Network Analysis* (eds. Burt, S. R. & Minor, M. J.) vol. 22 176–194 (1983).
50. Girvan, M. & Newman, M. E. J. Community structure in social and biological networks. *Proceedings of the National Academy of Sciences of the United States of America* **99**, 7821–6 (2002).
51. Lindblom, T., Mavruk, T. & Sjögren, S. East or west, home is best: The birthplace bias of individual investors. *Journal of Banking and Finance* **92**, 323–339 (2018).
52. The World Bank. *The Water Resources Sector Strategy*. (2003).
53. UNFCCC. *The Paris Agreement*. (2015).
54. United Nations. *Addis Ababa Action Agenda of the Third International Conference on Financing for Development*. (2015).
55. United Nations. *Transforming our world: The 2030 agenda for sustainable development UNITED NATIONS TRANSFORMING OUR WORLD: THE 2030 AGENDA FOR SUSTAINABLE DEVELOPMENT*. (2015).
56. Hodge, G., Greve, C. & Biygautane, M. Do PPP's work? What and how have we been learning so far? *Public Management Review* **20**, 1105–1121 (2018).
57. Ahmad, E., Dowling, D., Chan, D. & Godfrey, N. *Scaling Up Investment for Sustainable Urban Infrastructure: A Guide to National and Subnational Reform | Coalition for Urban Transitions*. (2019).
58. Finance in Common. *Joint Declaration of all public development banks in the world*. (2020).
59. G20. *G20 Operational Guidelines for Sustainable Financing*. (2017).
60. The Socialist Republic of Vietnam. *Vietnam's Intended Nationally Determined COntribution (INDC) updated version*. (2020).
61. India, R. of. *India's Intended Nationally Determined Contribution (INDC)*. (2016).
62. UNFCCC. NDC Partnership Forum Identifies Ways to Help Countries Recover Better. *NDC Partnership Forum* (2020).
63. OECD. *Multilateral Development Finance*. (2018). doi:https://doi.org/https://doi.org/10.1787/9789264308831-en.
64. Buhr, B. & Volz, U. *Climate Change and the Cost of Capital in Developing Countries - UNEP Inquiry*. (2018).
65. Farinosi, F. *et al.* Will the Paris Agreement protect us from hydro-meteorological extremes? *Environmental Research Letters* **15**, 104037 (2020).

Measuring the research-action gap in innovation for climate change in Europe[5]

1. Introduction

Climate change is an existential threat to the productive means of societies, but also to the livelihoods of human beings, their cultural heritage, behaviors and habits. Climate shapes the relationship between humans and nature and alters the conditions that allow societies to grow, develop and prosper. The inherent physical complexity of the climate, together with the pressure of anthropogenic activities, require long-term and comprehensive solutions capable of accounting for multiple factors. According to the IPCC, *"innovation and change can expand the availability and/or effectiveness of adaptation and mitigation options"*[1]. Innovation supports the climate risk reduction strategies (adaptation pathways) and offers technical solutions to reduce emissions (mitigation pathways). Hence, innovation is the enabling factor to support the technological and socio-economic progress, while also protecting the environment and preserving the local cultural traits.

Despite the potentialities, the mechanisms through which innovation triggers both adaptation and mitigation pathways are still poorly investigated. This is partly due to a lack of common understanding of what "innovation" entails. The concept is often confused with "invention", "novelty", and "change" [2]. The term appears with increased frequency not only in scientific literature but most and foremost in policy documents (i.e. The EU Green New Deal and the Mission-oriented innovation research agenda for the EU, among others). This trend increases the chances of transforming a powerful concept in a buzzword., limiting its potential. While there are multiple attempts of promoting economic frameworks to nurture innovation-led growth, it is unclear what kind of innovation is actually meaningful and worth investing in. The question is not limited to a better characterization of a concept, but also to its operationalization. The building blocks as shaped by research do affect people's lives in pervasive ways and this holds especially for innovation for climate-smart societies. Too often, innovation is considered as a technocratic and exclusive domain, while instead it is inherently political. It can induce incremental, radical and transformational changes through the networks of institutions that develop it and actors that adopt and spread it. Hence, it is

[5] This chapter is derived from Larosa, F., submitted for consideration in a peer-review journal of IF 5.085

not enough to detect how different forms and types of innovation contribute towards a climate-smart society; we are also asked to find how it is implemented in practice. Are priorities identified by research reflected in concrete innovation actions and incentives? Are there gaps between research and research policies in the realm of climate change? Where should policy strengthen existing links between disciplines? Are climate policy resources maximised or is there room for improvement?

This work addresses this twofold challenge by building the landscape of the European innovation system for climate change. I use a complexity approach, which embraces heterogeneity aspects in a holistic perspective [3]. I study the dynamics of two different layers (domains) of the landscape: scientific knowledge and implemented actions. Hence, I measure the distance between them to detect whether a research-action gap exists. I use a cost-effective machine learning methodology based on text mining which has scope for applications beyond our enquiry.

I unfold the innovation patterns throughout the years, by identifying how innovation for climate change has been presented in the body of scientific literature published over 40 years (1979-2020). I apply Natural language processing (NLP) to the abstracts of publications to build a network of interrelated topics that characterize the scientific universe covering climate change. I repeat the procedure to the abstracts of innovation actions funded under the European FP6, FP7 and H2020 programs and we represent them as a network of interconnected topics. The analysis of the network allows me to check whether links exist between different disciplinary approaches and branches and which topics are more central than others. I finally compute the lexical distance between the domains of research (literature) and action (projects) to inform European policy about existing gaps and missed opportunities.

This chapter offers policy-relevant insights about innovation for climate change through a rigorous and unique methodology. The chapter contributes to innovation studies at different levels. First, I quantitatively and qualitatively map the scientific knowledge produced in climate change and I follow it evolution overtime. Second, I compare and link this knowledge to the projects delivered in Europe to stress potential synergies and bottlenecks. From a policy perspective, the chapter opens an evidence-based and science-driven ground to improve the mission-oriented innovation policy framework recently launched by the European Commission. The approach used offers policy-makers an evidence-based overview to improve the efficiency of funding mechanisms while addressing the most urgent needs and to assess the effectiveness of public funds. Finally, the chapter contributes to the existing literature with a cutting-edge methodology, which combines machine learning and network science in a unified framework.

2. Materials and methods

The chapter retrieves data from two different sources. For the peer-reviewed literature, we use the bibliometric database Scopus. The corpus of publications is built by launching three large and combined queries that capture the historical evolution of concepts related to climate change (details are provided in the Appendix A)[6]. The three expressions capture: the jargon changed as the science progressed. The query embraces the shift from a pure "warming" idea to a more complex and transdisciplinary one: "change".

For the EU-funded innovation actions, I downloaded EU-funded projects under three frameworks: FP6, FP7 and H2020 from the European Commission Community Research and Development Information Service (CORDIS) database (https://cordis.europa.eu/en). The database contains information about the name and the id of the project, call, the program, the project's cost and the European maximum contribution to it, the coordinator's name and country as well as the participants to the consortium. Importantly, it contains the abstract of the project in the form of short text. I filter only climate innovation relevant projects by removing other areas of interest and by applying the same large query used for peer-reviewed literature.

I apply an unsupervised machine learning routine to both the abstracts of the research papers and innovation actions' ones. Written text offers valuable information about the linguistic, semantic and contextual nature of documents. The growing amount of literature, reports and written records in the space of climate action and climate innovation, reduces the easiness to turn information into usable knowledge. A convenient approach for the analysis of large text corpora stems in the use of topic models [7] or mixed membership models [8]. Topics are semantic "themes" generated by distributions of words belonging to a specific vocabulary. In mixed membership models, each document is described by multiple topics; the words in documents are assigned to single topics. Hence, documents are represented as vectors of words assigned to different topics according to an estimated proportion.

I use a Structural Topic Model (STM) to first detect the most relevant topics and then to quantify their potential connections. The STM [9] is an improvement of multiple topic modelling techniques including the Latent Dirichlet Allocation (LDA) [10], the Correlated Topic Model (CTM) [11] and

[6] (global warming" AND "innovation; "greenhouse gas effect" AND "innovation"; "climate change" AND "innovation") on Scopus in November 2020.

multiple extensions of these two [12–14]. The novelty of STM lies in its ability to discover the topical structure of the corpus estimating the relation of the topics with the documents' metadata (e.g. publication years, framework programs). As other topic models, STM is an "unsupervised" and data-driven method. STM does not ex-ante assume the optimal number of topics, nor their content. Instead, it infers them from data. Differently from standard LDA, STM achieves a better distribution of words in topics by exploiting the covariance with document-specific metadata.

The process is explained as it follows. Each document is a set of K topics, as in the standard LDA model. We estimate a distribution over topics (θ) to get topic proportions. Topics can be correlated with each other and their prevalence may vary because of a set of covariates W. This is particularly true in presence of a highly interdisciplinary field such as climate change innovation. The prevalence is estimated through a standard regression model where $W \sim LogisticNormal(W\gamma, \Sigma)$ and Σ is a $K-1$-by-$K-1$ covariance matrix. First, topic proportions are estimated by assigning words to the document-specific distribution of topics conditional to covariates W. For instance, we may be interested in topics proportion depending on the framework programme under which projects are funded. Words are then chosen from a multinomial distribution with parameter β, conditional to the topic assignment in the first step. The parameter β derives from deviations from the baseline of words distribution, which can vary because of a set of covariates $U \neq W$. For instance, we may find that topics related to "adaptation" to climate change" use frequently words like "resilience".

The STM has three core differences with standard LDA. The first is the potential correlation between topics; the second is the document-specific prior distribution over topics; the third is the presence of an additional set of covariates within topics $U \neq W$. The STM is a replicable and time-effective method with few a priori assumptions to be made. However, it requires a wide effort to interpret the topics as bags with word- and document-probabilities assigned.

I include different covariates per layer. In the peer-reviewed research layer, we split the database according to the IPCC Assessment Report (AR) it relates to (Table 1, Appendix A). I am interested in understanding if the timeframe to which the publication belongs influences to any extent the prevalence of some topics over others. As second set of covariates, I use the publication year to allow for annual heterogeneity within the sample. As for the set of EU-funded projects, I let the topics prevalence vary per framework programme under which projects receive funds (i.e. FP6, FP7 and Horizon2020).

The STM allows the identification of the topics characterizing both layers (i.e. peer-reviewed publications and EU-funded projects) and their connections. I am interested not just to intra-layer connections, but also to the distance inter-layer ones. Multiple areas of enquiry follow a complex dynamic. On one hand, topics can lead to aggregate phenomena that signal the strong interest of one layer towards new emerging properties. On the other, missed links and loosely connected topics highlight where efforts should be concentrated to strengthen the research-action collaboration.

First, I use the STM to compute links between topics and generate a network of interaction weighted on their correlation coefficient. I repeat the process for both layers separately. Then, I measure the distance between the two networks by computing the cosine similarity between topics belonging to the two layers. This approach measures how similar two pieces of text are based on their use of words sharing the same vocabulary (English in this case). The Cosine similarity ranges between 0 and 1. It is a metric computed between documents (say A and B) in a n-dimensional vector space, where every word is a vector:

$$\cos(\theta) = \frac{\sum_{i=1}^{n} A_i B_i}{\sqrt{\sum_{i=1}^{n} A_i^2}\sqrt{\sum_{i=1}^{n} B_i^2}}$$

The measurement of the distance between the layers and their connections brings new insights to the literature. On one hand, it offers a fast and effective way to estimate the research-action gap. This approach could potentially be applied to other domains of enquiry, beyond climate change innovation. On the other hand, we observe how connections and links between diverse topics fill existing gaps. The collective emerging properties of the networks are observed and the difference between the two layers under scrutiny. By doing so, we achieve a comprehensive view of climate change innovation and contributes to enabling a stronger interaction between theory and action.

3. Results

3.1.The state of research on climate innovation

For peer-review literature, I obtain 6018 initial observations. After cleansing and duplicates removal, the database included 5556 records (Table 3) published in over more than 40 years (1979-2021). After remaining substantially stable in the first decade, interest towards innovation for climate change has witnessed an exponential growth (Figure 12). This may be due not only to the general increase in academic production that affected almost any research discipline, but also the nature of this existential threat and to the progresses in understanding the causes of this irreversible process After the Kyoto protocol signature (1999), research embraced a solution-oriented approach which involved scientists from different fields and marked by two milestones In fact, social scientists entered the climate debate also thanks to the publication of The Stern Review (October 2006) and the momentum expanded further after The Paris Agreement in 2015, when countries strongly committed to keeping the temperature below 2C target. These pivotal events are also justifying the large interest we observe in technology and the strong call for emission reduction and energy transition.

Table 3 | Descriptive statistics of the peer-reviewed publication domain

Documents	5556
Sources (Journals, Books, etc.)	2616
Keywords Plus (ID)	17965
Author's Keywords (DE)	11945
Period	1979 - 2021
Average citations per documents	16.84
Authors	15362
Author Appearances	18312
Authors of single-authored documents	1400
Authors of multi-authored documents	13962
Single-authored documents	1617
Documents per Author	0.362
Authors per Document	2.76
Co-Authors per Documents	3.3
Collaboration Index	3.54

From a research perspective, the Intergovernmental Panel on Climate Change (IPCC) became a guide to policy because of the publication of the Assessment Reports (ARs), a six-year review of the existing knowledge and science on climate change. I split our database respecting the publication date of each ARs and we computed the dynamic complexity of the text by using lexical diversity. I also include the last-published records (up to 2021) acknowledging that AR6 is still a work in progress. Given the fast-rate progresses in the field, these publications (1210) are a precious subset in our study.

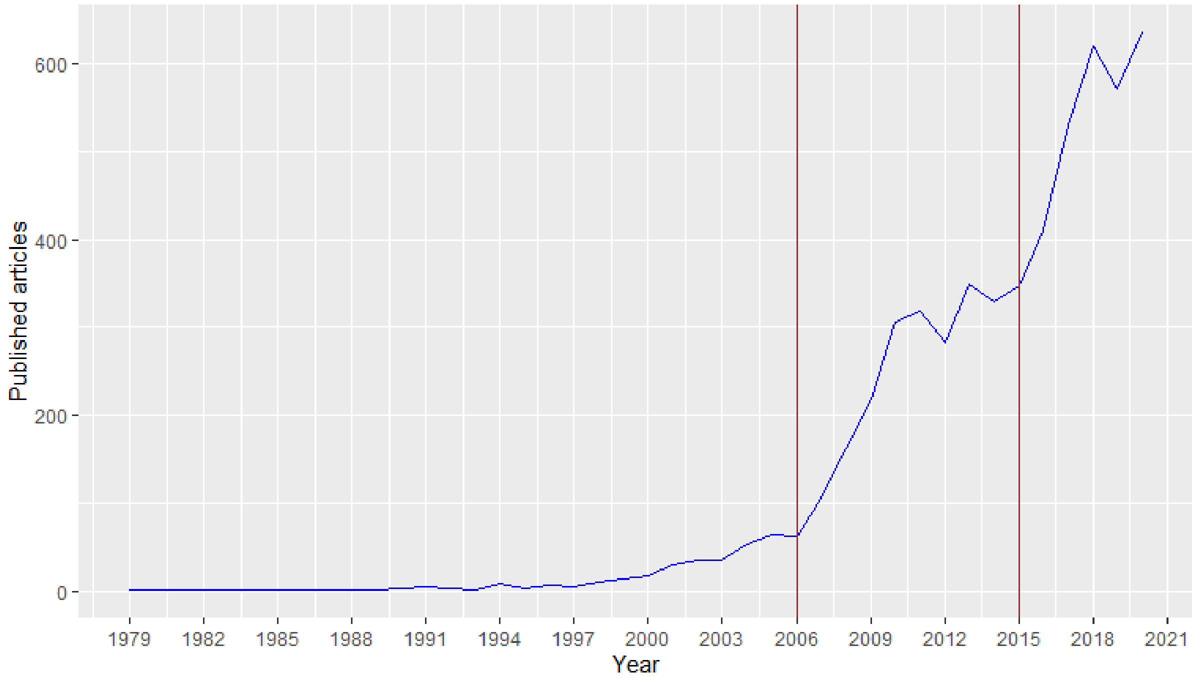


Figure 12 | The scientific production in innovation for climate change

The lexical diversity signals the variety of topics and words: if increasing, this means there is a wider composition of new terminologies and jargons entering the field. As by Figure 13, the amount of distinct words raises especially with the publication of AR5 (2014). This report first introduces the need to limit the global temperature below 1.5C to avoid incurring in a number of climate change impacts. The report explores pathways to reach the target and provided a detailed overview on the role of technologies (including negative emission technologies, NETs) in advancing solutions to climate change. However, findings were scattered in different sections and hard to find. It was only with the IPCC Special Report on Global Warming of 1.5C (2018) that this knowledge gathered together. The report advocated the NETs – defined in the report as "carbon dioxide removal (CDR) technologies – "on the order of 100-1,000GtCO2 [billion tonnes] over the 21st century." [15].

The heterogenous evolution is well captured by the most frequently used words across different IPCC ARs. Prior to the '90s (AR1) the climate innovation research put strong emphasis on the scientific background and knowledge about climate change impacts on biochemical processes and ocean dynamics. Innovation here takes the form of experimental approaches to better frame the problem and pave the road. The second IPCC AR timeframe shifted the attention towards energy generation and use.

The most locally cited record in this timeframe[16] explores the energy solutions of the future accounting for their social, technical and economic constraints and opportunities. Between 1995 and 2000 (AR3 timeframe) economists entered the debate.

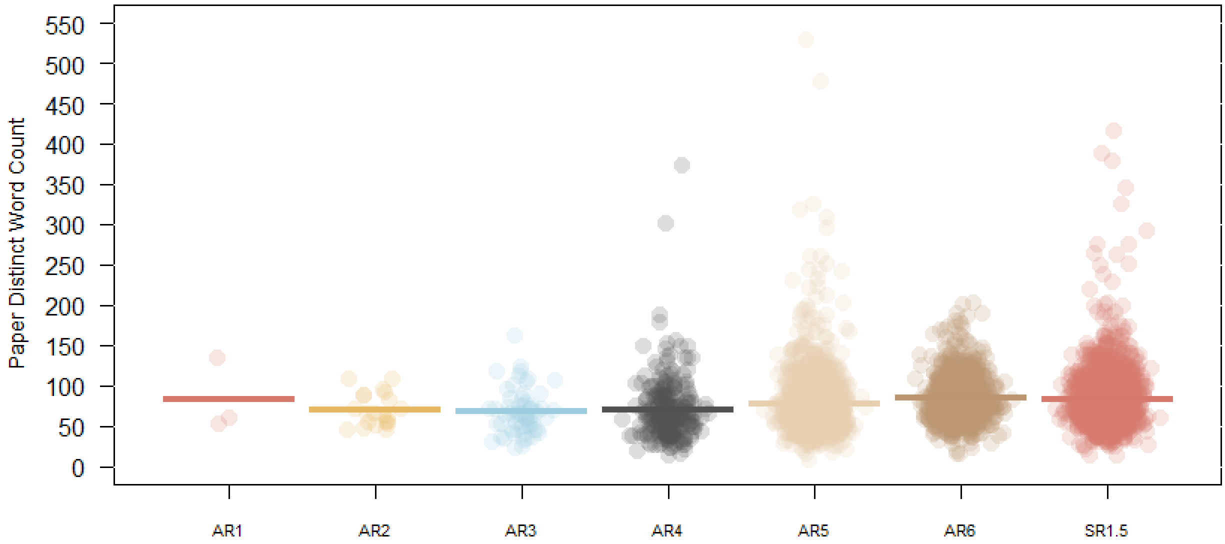


Figure 13 | The lexical diversity of peer-reviewed articles per IPCC Assessment Report

Among the top cited in this period, some papers tackled the research frontier in climate economics and policies [17–19], while others explored the challenges in modelling technological change [20,21]. Policy innovation became the priority focus for the following six years (AR4): choosing the right policies to promote the energy transition [22], promoting the best response from businesses [23,24] and improving the modelling approaches to technological change [25–27] became priorities for the research community. On the other hand, science progressed in addressing the need for improved climate forecasts in water resource management [28], advancing the atmospheric data assimilation processes [29] and exploring the connections between the present and the climate of the past [30]. The entrance in the new decade (2007-2013, AR5) is characterized by the role of technology but this time there is a significant interest in sector-specific requirements: nanotechnologies in water usage and reuse [31], transports [32] and rain-fed agriculture [33]. Worth noticing is the methodological focus on innovation systems [34], community-based approaches [35] and complexity [36]. Research published from 2015 (SR1.5 and in progress AR6) looks at the transition towards a climate-neutral economy by tackling innovative energy production processes [37–41] and the role of essential climate variables in policies and applications [42]. This higher specialization of topics calls for a strong reflection on interdisciplinarity, but also signals how specific science-based solutions can be.

To complement the picture offered by the bibliometric analysis, I apply the STM to the peer-reviewed publications set. After a documented process of fine-tuning, I find 34 topics (Table 2, Figure 1, Appendix A) that describe the bulk of climate change innovation as presented by research. The research topics relate to three dimensions of enquiry: adaptation, mitigation and product innovations with high and low technological intensity.

I observe a growing interest (Figure 2, Appendix A) in adaptation tools and practices, which include blue and green infrastructure (Topic 15), improved water resource management practices and tools (Topic 16), climate-smart genetically modified crops (Topic 25) and novel assessment methods (Topic 32). On the other hand, mitigation-related topics present a declining trend with the exception of innovations targeting vulnerable and developing countries (Topic 10), low-carbon technologies in China (Topic 19) and energy efficiency technologies (Topic 29). Research has increasingly questioned governance structure of climate change (Topic 27) and has progressively suggesting new and cost-effective ways to tackle technology (Topic 30). A steady growth of research published around biomass and bioproducts (Topic 22) is remarkable and a sustained interest for climate services (Topic 33) and health-related risk mitigation tools (Topic 9). This landscape suggests a progressive interdisciplinary attitude towards innovation and a lower focus on materials and industrial products to limit global warming. Furthermore, it signals there is wide room for economists (Topic 18) to tackle viable solutions while meeting the society's needs.

Beyond the simple investigation of core topics in the research domain, I am interested in mapping their connections. I find that topics devoted to governance and process innovation are directly linked to climate services and tools which result from interdisciplinary competences (orange bubbles, Figure 14). Adaptation and information services require a strong co-generation process in place, which may result in novel structures and new actors involved. I also find that topics related to energy-intensive sectors (i.e. transport and electricity production) are linked to each other and signal the need for business innovation and large-scale diffusion of technologies (green bubbles, Figure 14). The third highly connected group (blue bubbles, Figure 14) highlights that researchers pay attention to the complex human-nature interaction when promoting solutions to fight climate change. It is the case of nature-based solutions, but also to climate-smart agriculture and blue and green infrastructure (Figure 14).

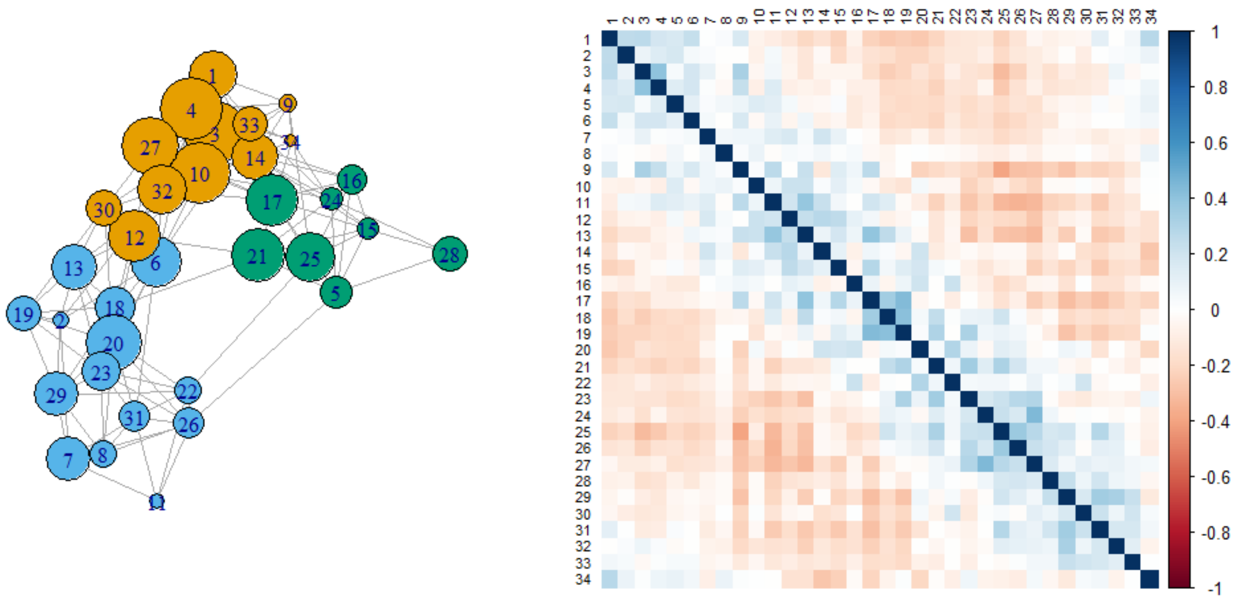


Figure 14 | The topic correlation in the research universe. Left-hand side: the three clusters of topics and their interactions. Nodes size reflect the prevalence of topics. Topic 12 includes all non-pertinent words of our sample and as expected it links all three groups. Right-hand side: the correlation plot presents the links weights: the strongest the blue, the tighter the probability of two topics to appear together in a document

3.2.Assessing EU action priorities

I extract 2067 projects spanning the 2004-2020 timeframe articulated as follows: 198 under FP6, 918 under FP7 and 951 under H2020.

Following the same methodology presented for scientific papers, I find 33 core topics describing the corpus of EU-funded projects (Table 3, Appendix A). Among them, the best represented topics relate to the next generation of Earth monitoring tools, climate services and nature-based solutions (Figure 5, Appendix A). I observe a growing number of projects involved in technological development, including progresses in the transport industry (Topic 11), improved ways to generate and distribute electricity (Topic 16), new materials to achieve energy efficiency (Topic 20). Adaptation-related innovations gained popularity with time. This is the case for energy efficiency and circular economy solutions in urban areas (Topic 13), climate smart crops and transformations in agriculture (Topic 18), nature-based solutions (Topic 26) and risk mitigation innovations in case of flood events (Topic 25). I also observe a growing number of projects related to bioenergy and agrifood solutions (Topic 29) as well as raising interest in biodiversity impact assessments through data-driven applications (Topic 33). I confirm the declining trend towards mitigation-related technologies and innovations.

I map the links between different topics mirroring the procedure we used for the corpus of peer-reviewed publications. I find four groups that represent meta-topics each describing a different dimension of innovation actions (Figure 15). The first tackles next generation solutions for industrial applications and market-ready tools in energy, agriculture and health. This domain (in orange in Figure 15) include bioenergy and energy efficiency, but also new materials and advancements in industrial processes. The second meta-topic (blue bubbles in Figure 15) describes innovation in cities and co-production approaches that account for interdisciplinary insights. Here, topics address flood risks in urban areas, nature-based solutions, local energy communities and multi-level governance of innovation. The third group (yellow bubbles in Figure 15) include procedural and methodological advancements, including new ways of monitoring air quality, novel understanding of atmospheric processes and lessons learnt from the assessment of the climate of the past. The fourth group (green bubbles in Figure 15) comprises innovation in adaptation to climate change. Here, climate services, early-warning systems, ecosystem services and novel Earth monitoring system tools are linked together. I find that majority of the most represented topics fall into this cluster: biodiversity impact assessments, climate services and ecosystem services are dominant.

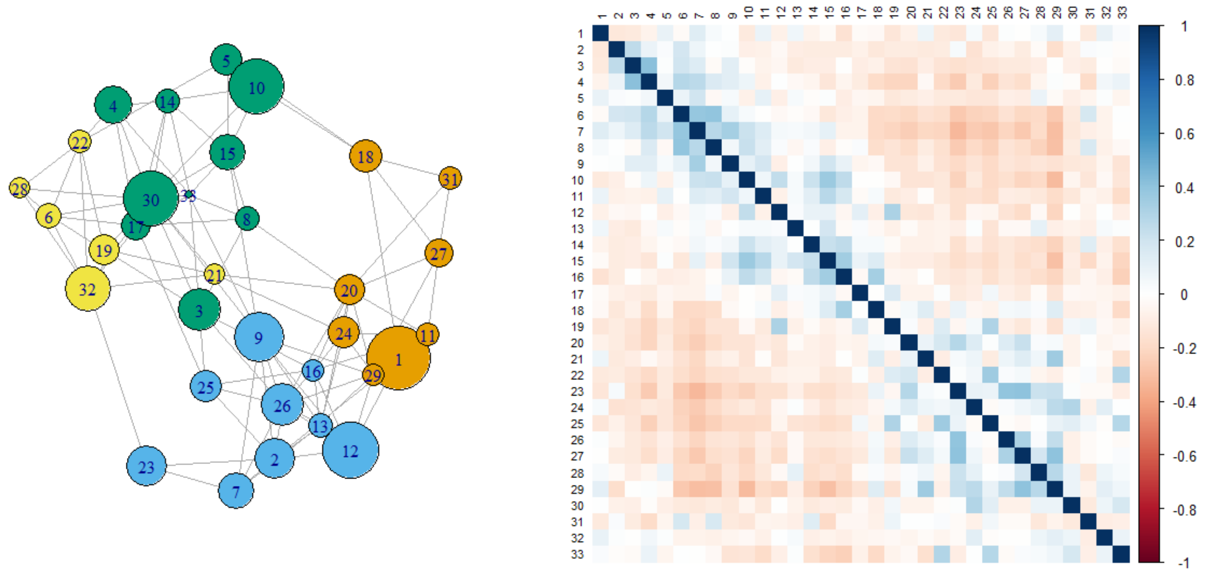


Figure 15 | The topic correlation in the project universe. Left-hand side: the four clusters of topics and their interactions. Nodes size reflect the prevalence of topics. Topic 21 includes all non-pertinent words of our sample and as expected it links all groups. Right-hand side: the correlation plot presents the links weights: the strongest the blue, the tighter the probability of two topics to appear together in a document

3.3.Measuring the research-action distance

The network of research topics is denser (0.2245) than the projects' one (0.1988) proving there is a slightly stronger contamination between different areas of work[7]. There are notable differences in the composition of the topics' clusters (Figure 6, Appendix A). Economic incentives and price mechanisms are strongly bonded to energy efficiency and low-carbon technologies in the research domain. Hence, they are seen as enablers of large-scale diffusion of mitigation practices. In the project domain, economic instruments, models and theories are associated to transformation pathways. They serve to value nature-based solutions and to improve energy efficiency in cities.

Agriculture also marks a discrepancy between the two domains. In the corpus of peer-reviewed publications, the agri-food sector mainly interacts with adaptation-related topics. The cosine similarity reveals that improved water resource management and smart solutions to climate-related variables are quite related to agriculture (similarity equal to 0.40 and 0.34 respectively). Agriculture, biomass and bioenergy production are less similar (0.20). On the contrary, projects tackle agriculture to reduce its impact on the environment. Climate-resistant crops and transformations in agriculture are addressed in tandem with biodiversity preservation (cosine similarity = 0.73) and freshwater ecosystem (cosine similarity = 0.38).

The third remarkable difference relates to innovations in industrial processes and new materials. The peer-reviewed documents investigated the opportunities derived from life-cycle assessment methodologies and focused on assessing the environmental performance trends in the most energy-intensive industries, such as transport and electricity production. The topics in the projects' set cover innovations and solutions to reduce emission in other industries, such as aviation and agriculture. Both domains include energy efficiency improvements, but the projects' one stresses the market readiness of these solutions.

The cosine similarity-based distance measure provides an understanding of where major research-action gaps are. While domain-specific connections are comparable, some topics lack the adequate inputs for research and/or implementation in innovation actions (Table 4). Research progresses in biomass and bioproducts (R22) have room for improvement. This topic includes the forest products industry and biorefining. A loosely connected area of work relates to innovation in agriculture. Here, research investigated over biotechnology-led approaches to uplift agricultural production, but also questioned the most appropriate methods to support climate-stressed developing countries (R25).

Connected to it, also research in risk mitigation and adaptation practices failed to find adequate application (R17). This research topic strongly looks at emerging economies and vulnerable areas of the world. Climate-smart practices under scrutiny include transformative approaches, new business models, nature-based solution, innovative water contracts and target investments in the forestry sector.

Table 4 | The least connected topics in the research and project domains

Domain	Topic	Content
Research	22	Biomass and bioproducts
Research	25	Genetically-modified crops and innovations in the agricultural sector
Research	17	Enabling innovative adaptation to reduce vulnerability and mitigate climate change risk
Research	8	Innovations in the transport sector to become climate-smart
Research	5	Smart solutions to face essential climate variables changes
Projects	24	Models and tools for carbon and GHG emissions
Projects	25	Flood risk assessments: early warning systems and tools
Projects	29	Bioenergy and agri-food solutions
Projects	27	Innovations in the agroforestry systems
Projects	20	Market-ready new materials for energy efficiency

On the projects' domain, different innovation actions would require stronger research and theory-based inputs. It is the case of engineer-based processes to recover and convert greenhouse gas emissions (P24). Projects develop solutions for carbon capture and storage, electrocatalytic conversion of CO2 into chemical energy carriers, as well as new CO2 capture processes by innovative absorbents based on novel aerogels. All these products could be studied to test their efficiency and their usability in diverse contexts. The same dynamics happen for flood risk assessments and risk intelligence services, which are now becoming the norm especially in urban areas. These tools suffer from pressing market barriers that prevent their successful upscale. Research can help identifying the most pressing limiting factors to overcome them and move from useful to usable science.

The last two under-connected topics would benefit from a stronger science-policy interface. EU-funded projects piloted and tested the combination of management practices – such as sustainable water usage and combined approaches - and genetic diversity in different areas of the world (P27). Also, projects explored technologically enhanced materials to increase climate resilience. Lessons learnt could feed the research-policy interface and constitute valuable seeds to inform new research designs.

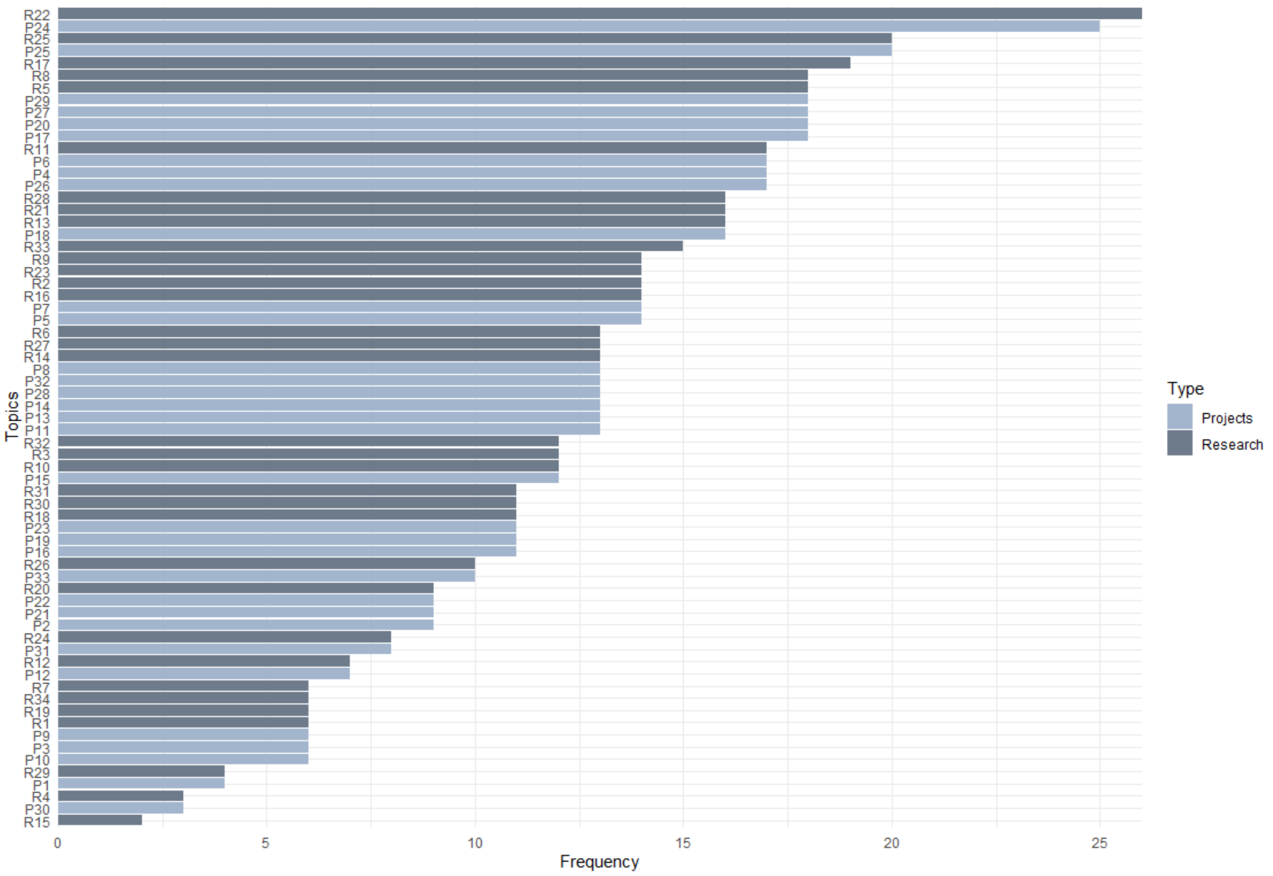


Figure 16 | The least connected topics in the research and policy domains. We compute the frequency of low (cosine similarity < .5) lexical similarity between topics belonging to two separate domains. Despite the numerosity of connections, the least connected topics are those weakly connected to others in the second domain.

4. Discussion and conclusion

Science-based and socially equitable climate innovation has never been more urgent. National, European and international policy frameworks encourage a change of perspective putting climate at the center of a new sustainable living. The European Green Deal calls for fostered "deployment of innovative technologies and infrastructures" (Section 2.1.2., [43]) and the US Green New Deal – without explicitly mentioning the term "innovation" lists the widespread needs top "invest in the infrastructure and industry of the United States to sustainably meet the challenges of the 21st century" (pg. 5, [44]).

Innovation is a process that leads to a "creative destruction" [45] capable of transforming the way the productive means works. Innovation is a chain that takes "time and money"[46]. It begins with invention and it develops with R&D, failures and tests. Research does not just provide advancements in methods, but also opens to new stakeholders, approaches, and needs. As such, a productive dialogue between research and practice can lead to new emerging and previously unexplored pathways.

In this work, I measure the research-action gap in climate innovation. I explore to what extent and how the academic progresses – as described by the corpus of peer-reviewed literature in the field – is perceived and applied in European funded innovation projects. The focus on the EU innovation actions has a double motivation: the mission-oriented European framework aims at shifting from useful to usable science to achieve the milestone missions of at least the next framework. Moreover, the open data policy of the European Union provides us with the rare opportunity of a wide database of detailed projects. I leave the research layer of our investigation open to extra European contributions because published records do not know boundaries and their exploitation is not restricted to specific geographical areas.

While this chapter approach contributes to the existing literature in innovation studies, results can inform the European climate change policy. I find a declining interest in mitigation-related technologies, confirming existing studies [47], but a growing interest in adaptation measures including blue and green infrastructures. This trend may suggest that at least part of the low-carbon energy technologies developed in the past are now mature for their reference market [47]. On the other hand, the raising focus on adaptation and risk mitigation solutions flags that impacts have been and will continue to be felt across the world.

Among the findings, two call for stronger attention from policy making. First, the research and action layers differ in the way different topics link to each other. For instance, research has explored economic tools (*i.e.* prices and incentives) mostly in connection to energy efficiency and low-carbon technologies, while much has to be done in the adaptation sphere. This includes economic assessments and evaluation of existing projects from a scientific perspective. Evidence in this sense would boost the diffusion of good practices showing what works and in which contexts. Similarly, projects can make wider use of interdisciplinary research. This holds for agriculture and improved use of natural resources, where research has important lessons learnt still poorly explored by EU projects.

Secondly, the distance between research and action reveals that there is room for improvement in the areas of large-scale agriculture, industrial applications and risk assessments. I find that a tighter collaboration with the industry and private players could play a role in advancing the uptake and diffusion of climate-smart innovations. In agriculture, climate-resistant crops can guarantee food security and increased resilience to the most vulnerable. A stronger cooperation between researchers, civil society and decision-takers could boost the development and test of these applications while also protecting biodiversity and limiting the negative environmental consequences of their exploitation. I find that the distance is mostly due to projects' limits, hence suggesting that some of the research findings could be better incorporated in the actions.

As for industrial applications, I find a significant research-action gap in bioproducts. Here, a tighter cooperation with industrial players and the private sector would lead to standards, certificates and shared practices that projects often develop with insufficient support from research. This holds for business model and market innovation.

Finally, research and action can cooperate over risk assessment and especially flood risks. Here, projects can serve to collect granular exposure and vulnerability data serving as seeds for punctual and precise models. Basic and applied research should be supported to deliver actionable knowledge and to increase the accuracy of climate projections and forecasts. On the other hand, projects can act as interfaces with stakeholders to promote a climate-aware and risk-conscious culture.

References

1. IPCC. *Climate Change 2014: Synthesis Report. Contribution of Working Groups I, II and III to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change*. (2014).
2. Ruttan, V. W. Usher and Schumpeter on Invention, Innovation, and Technological Change. *The Quarterly Journal of Economics* **73**, 596 (1959).
3. Pugliese, E. *et al.* Unfolding the innovation system for the development of countries: coevolution of Science, Technology and Production. *Scientific Reports* **9**, 1–12 (2019).
4. Field, C. B. *et al.* Summary for policymakers. in *Climate Change 2014: Impacts,Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change* 1–32 (IPCC, 2014).
5. Bosetti, V., Carraro, C., Massetti, E. & Tavoni, M. *Climate change mitigation, technological innovation and adaptation : a new perspective on climate policy*. (2014).
6. O'Brien, K. & Sygna, L. Responding to climate change: The three spheres of transformation. in *Proceedings of Transformation in a Changing Climate* 16–23 (2013).
7. Blei, D. M. Probabilistic topic models. *Communications of the ACM 55* **4**, 77–84 (2012).
8. Airoldi, E. M., Blei, D. M., Erosheva, E. A. & Fienberg, S. E. *Handbook of Mixed Membership Models and Their Applications*. (2014).
9. Roberts, M. E., Stewart, B. M. & Airoldi, E. M. A Model of Text for Experimentation in the Social Sciences. *Journal of the American Statistical Association* **111**, 988–1003 (2016).
10. Blei, D. M., Ng, A. Y. & Jordan, M. Latent Dirichlet Allocation. *Journal of Machine Learning Research* **3**, 993–1022 (2003).
11. Blei, D. M. & Lafferty, J. D. A correlated topic model of Science. *The Annals of Applied Statistics* **1**, 17–35 (2007).
12. Paul, M. & Dredze, M. SPRITE: Generalizing Topic Models with Structured Priors. *Transactions of the Association for Computational Linguistics* **3**, 43–57 (2015).
13. Ahmed, A. & Xing, E. P. Timeline: A Dynamic Hierarchical Dirichlet Process Model for Recovering Birth/Death and Evolution of Topics in Text Stream. in *Proceedings of the Twenty-Sixth Conference on Uncertainty in Artificial Intelligence* (2010).
14. Eisenstein, J., Ahmed, A. & Xing, E. P. Sparse additive generative models of text. in *Proceedings of the 28th International Conference on International Conference on Machine Learning* 1041–1048 (2011).
15. IPCC. *Special report on Global Warming of 1.5 °C* . (2018).
16. World Energy Council. *Energy for Tomorrow's World: The Realities, the Options and the Agenda for Achievement:* (1993).
17. Grubb, M., Chapuis, T. & Duong, M. H. The economics of changing course. Implications of adaptability and inertia for optimal climate policy. *Energy Policy* **23**, 417–431 (1995).
18. Toman, M. Research frontiers in the economics of climate change. in *Environmental and Resource Economics* vol. 11 603–621 (Kluwer Academic Publishers, 1998).
19. Agrawala, S. Early science-policy interactions in climate change: Lessons from the Advisory Group on Greenhouse Gases. *Global Environmental Change* **9**, 157–169 (1999).
20. Weyant, J. P. & Olavson, T. Issues in modeling induced technological change in energy, environmental, and climate policy. *Environmental Modeling and Assessment* **4**, 67–85 (1999).
21. Grübler, A., Nakićenović, N. & Victor, D. G. Modeling Technological Change: Implications for the global environment. *Annual Review of Energy and the Environment* **24**, 545–569 (1999).
22. Menanteau, P., Finon, D. & Lamy, M. L. Prices versus quantities: Choosing policies for promoting the development of renewable energy. *Energy Policy* **31**, 799–812 (2003).
23. Kolk, A. & Pinkse, J. Business Responses to Climate Change: Identifying Emergent

Strategies. *California Management Review* **47**, 6–20 (2005).
24. Kolk, A. & Pinkse, J. Market strategies for climate change. *European Management Journal* **22**, 304–314 (2004).
25. Popp, D. ENTICE: Endogenous Technological Change in the DICE Model of Global Warming. *Journal of Environmental Economics and Management* **48**, 742–768 (2004).
26. Van Der Zwaan, B. C. C. *et al.* Endogenous Technological Change in Climate Change Modelling. *Energy Economics* **24**, 1–19 (2002).
27. Grubb, M., Köhler, J. & Anderson, D. Induced Technical Change in Energy and Environmental Modeling: Analytic Approaches and Policy Implications. *Annual Review of Energy and the Environment* **27**, 271–308 (2002).
28. Rayner, S., Lach, D. & Ingram, H. Weather forecasts are for wimps: Why water resource managers do not use climate forecasts. *Climatic Change* **69**, 197–227 (2005).
29. Houtekamer, P. L. *et al.* Atmospheric data assimilation with an ensemble Kalman filter: Results with real observations. *Monthly Weather Review* **133**, 604–620 (2005).
30. Richerson, P. J., Boyd, R. & Bettinger, R. L. Was Agriculture Impossible during the Pleistocene but Mandatory during the Holocene? A Climate Change Hypothesis. *American Antiquity* **66**, 387–411 (2001).
31. Qu, X., Alvarez, P. J. J. & Li, Q. Applications of nanotechnology in water and wastewater treatment. *Water Research* **47**, 3931–3946 (2013).
32. Chapman, L. Transport and climate change: a review. *Journal of Transport Geography* **15**, 354–367 (2007).
33. Cooper, P. J. M. *et al.* Coping better with current climatic variability in the rain-fed farming systems of sub-Saharan Africa: An essential first step in adapting to future climate change? *Agriculture, Ecosystems and Environment* **126**, 24–35 (2008).
34. Weber, K. M. & Rohracher, H. Legitimizing research, technology and innovation policies for transformative change: Combining insights from innovation systems and multi-level perspective in a comprehensive "failures" framework. *Research Policy* **41**, 1037–1047 (2012).
35. Seyfang, G. & Haxeltine, A. Growing Grassroots Innovations: Exploring the Role of Community-Based Initiatives in Governing Sustainable Energy Transitions. *Environment and Planning C: Government and Policy* **30**, 381–400 (2012).
36. Pahl-Wostl, C. The implications of complexity for integrated resources management. *Environmental Modelling and Software* **22**, 561–569 (2007).
37. Nikolaidis, P. & Poullikkas, A. A comparative overview of hydrogen production processes. *Renewable and Sustainable Energy Reviews* vol. 67 597–611 (2017).
38. Deng, J., Li, M. & Wang, Y. Biomass-derived carbon: Synthesis and applications in energy storage and conversion. *Green Chemistry* vol. 18 4824–4854 (2016).
39. Jadhav, S. G., Vaidya, P. D., Bhanage, B. M. & Joshi, J. B. Catalytic carbon dioxide hydrogenation to methanol: A review of recent studies. *Chemical Engineering Research and Design* vol. 92 2557–2567 (2014).
40. Gielen, D. *et al.* The role of renewable energy in the global energy transformation. *Energy Strategy Reviews* **24**, 38–50 (2019).
41. Zhang, X. *et al.* Managing nitrogen for sustainable development. *Nature* vol. 528 51–59 (2015).
42. Bojinski, S. *et al.* The concept of essential climate variables in support of climate research, applications, and policy. *Bulletin of the American Meteorological Society* **95**, 1431–1443 (2014).
43. European Commission. *The European Green Deal*. *COM/2019/640 final* (2019).
44. The House of Representatives. *116th Congress 1st Session H. Res. 109*. *US Government* (2019).
45. Schumpeter, J. A. *The theory of economic development : an inquiry into profits, capital,*

credit, interest, and the business cycle. (Harvard Economic Studies, 1934).
46. Grubb, M. *Planetary Economics*. (Routledge, 2014).
47. International Energy Agency (IEA) & European Patent Office (EPO). *Patents and the Energy Transition*. (2021).

Business models for Climate Services: an analysis[8]

1. Introduction

Substantial efforts have been made in recent years to develop and foster use of climate-services for climate adaptation policy and decision making. Defined as “timely production, translation and delivery of useful climate data, information and knowledge”[1], climate services and products embrace climate records, catalogues of extreme events, reanalyses, forecasts, projections and indices used in vulnerability and risk assessments. Given the growing interests and application in many sectors[2–4], development of climate services has progressively shifted away from top-down, supply-driven (pushed) towards user-centric and -tailored (pulled) innovation processes. This has helped climate services’ projects to overcome the “valley of death”[5], a critical stage between prototype and operational phase in which resources are often lacking to launch a product or make it fully operational[6].

Climate services require novel approaches to reach those who need it most [7,8]. Inadequate engagement of users stood as a barrier preventing greater adoption for individual and collective decision making[9]. Research has identified business models as tools to close this gap: they enhance innovation[10,11], support sustainability[12] and overcome barriers in the product development stage[11]. They link production and consumption sides[10,13] and function as market devices[14].

In this chapter I explore critical factors behind business models using a sample of 32 climate services. The set comprises ongoing and completed collaborative innovation projects, but also in-house innovations of single businesses. I conduct semi-structured interviews with senior-level managers, using the business model canvas (BMC) as a framework. BMC makes it possible to identify nine components that are constantly interacting and evolving throughout the life span of a service. I revise the standard BMC and added two cross-case building blocks that are important for an embryonal market. I employ content analysis and assigned codes to various token of the transcribed interviews. By using graph theory and network analysis, I assess the relationship between key topics, representing

[8] This chapter is derived from Larosa, F. and Mysiak, J., 2020. Business Models for Climate Services: an analysis. Climate Services, 17. https://doi.org/10.1016/j.cliser.2019.100111

them in a directed graph where nodes are codes and links are weighted on the proximity between words in each token of text.

This chapter represents one of the first attempts to analyse the role of business models for deployment of climate services. To do so I combine several methods within a consistent analytical framework.

2. Business models: a multi-purpose tool

2.1.Defining business models

A business model is a "representation of firms' underlying core logic and strategic choices for creating and capturing value within a value network" [15]. How a company generates and retains value is a part a business strategy. Value network constitutes a space for interaction with clients, suppliers, purveyors, donors and civil society[15]. By serving as "market device"[14], business models help to mobilise internal (e.g. skills, knowledge and financial resources) and external (e.g. access to financial capital) resources and promotes new ways of sustainable innovations[11,13,16].

Research on business models identified three recent evolutionary streams[17]. The first, technology-driven stream originates in the dot-com era. Rapid increase of web-based products and online platforms initiated "e-business models". In a second stream, business models are used as tools of strategic management, by proving their relevance in boosting the positioning of a company along the value chain. Instead of focusing on product innovation alone, researchers identified the role of process innovation and changes in enhancing productivity ceteris paribus. These changes are addresses by business models and their building blocks[18]. The third stream places emphasis on market competition[11]. Business model innovation sets off a new field of competition, complementary to the value proposition [19]. As a result of incremental changes in value network and customers' segments, two comparable products may gain different shares of the market only because of the business model they use.

Business models are triggers of innovation capable of creating new realities [20]. This is done by supporting ideation, development and marketing of innovations characterised by disruptive forces: new services in a new market or new services capable of re-shaping existing business dynamics [21]. In the context of climate services, business model innovation stimulates growth of efficient, policy-oriented and science-informed business ecosystems. Finally, business models for climate services also serve an educational purpose: they empower stakeholders to share best practices, data and protocols [22,23], contributing so to expanding the available knowledge stock.

2.2.Climate services as sustainable knowledge-intensive business services

Climate services can be seen as a form of sustainable innovation which "takes into account environmental, social and economic considerations in their development and use" [24]. Business models are critical for the success of climate services [13]. Sustainable innovations can be technological, organisational and social [10]. Business models shape the internal organisational processes, supporting effectiveness in linking providers and users. Also, they help maximising the collective utility achieving social maxima through technological transformations. The analysis of existing literature suggests that business models act as signals and mediators within a given market, often leaving the revenue model behind, while positively impacting on society [10,14].

Climate services are a special type of knowledge-intensive business service (KIBS), i.e. non-financial, knowledge-intense services characterised by high human capital density [25,26]. They are intangible and difficult to standardise [27]. Progressive shift from industrial to service-dominated economies (tertiarization) has favoured knowledge industries and climate services are part of this transformation [28]. KIBS do not just generate new products and services, they also support co-production of innovation [29]. They have in common three features:

- Knowledge is both input and output of knowledge-intensive services. Knowledge comprises a whole "stock of expertise"[30], including context-specific judgements and choices. This is why standardisation of KIBS is difficult.
- Services are products of close and multiple interactions between providers and clients, implicit to co-creation process [31], and final services are tailor- and custom-made to the specific knowledge demand of customers [32].
- Systemic understanding of innovation include product/service development, marketing strategies and innovative work practices [33]

Climate services include these features and incorporate them in business models [23]. However, literature revealed three main barriers:

- Co-development of climate services need to be cultivated, and the added value of services explored from the beginning [16,34]
- Business models are often ineffective and not adapted to profit-oriented and private sector's culture [22]

- Asymmetries in benefits and gains across separate groups must be tackled in order to equally understand the implications of providing timely and accurate climate information to society [35]

Mitigation practices found a relatively successful window of opportunities so far [22], while the market for adaptation is also promising at the early stage of development. A variety of actors and organisations are supplying climate services [36] for a wide spectrum of economic and policy sectors. The uptake of climate services is driven not just by the knowledge product itself. Clear identification of the value-proposition (advantages gained by users) is equally important. Finally, service providers can be simultaneously suppliers and users of climate services, making the identification of stakeholders difficult [37].

2.3.The Business Model Canvas

This chapter adopts the Business Model Canvas[38] as a framework for analysis. Business Model Canvas (BMC) is described by nine components (Figure 17). The left side of the 'canvas' reflects the product-related components, whereas the right side is focused on the customers' side. Value proposition, characterized as "the bundle of products and services" [38] aimed at satisfying users' needs and creating value, is located in-between.

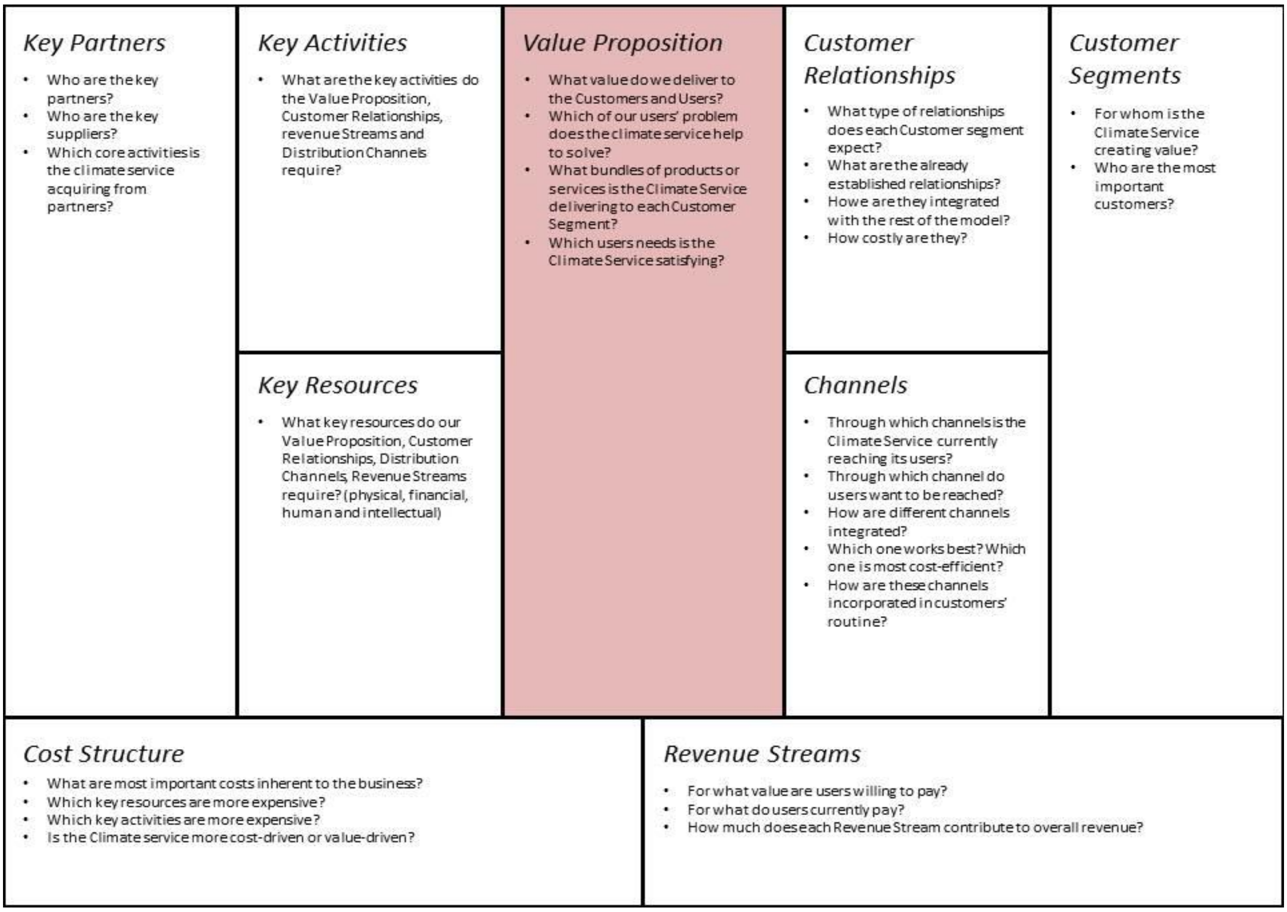


Figure 17 | Business Model Canvas

The BMC has found widespread application [13,39,40] and generally positive experience [13,41,42] but also some criticisms. BMC underscores how a company's value network operates. A value network (Figure 18) allows to share information, data, good practices and protocols, as well as to sell and buy products and services. It is defined as business ecosystem in which each member has a precise role and is continuously affected by interactions with other members [43,44]. Value is generated as a cumulative result of each participant's effort.

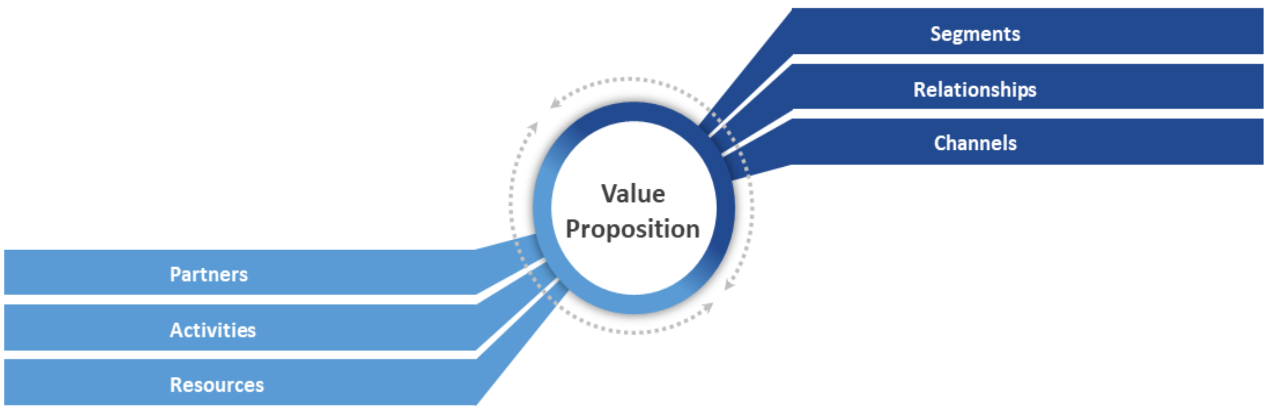


Figure 18 | Defining the value network

The value network (Figure 18) is composed by supply/provider (Figure 18, on the right) and demand/customer sides (Figure 18, on the left). Partners entail all stakeholders, suppliers and providers that ‘make the business model work’. Successful partnerships are forged as strategic alliances, are embedded in contingent risk strategies helping businesses to cope with market uncertainties. Partnerships are developed as non-competitive agreements, but they also include provider-user relationships. Operational activities deliver the value proposition and reach target users in the most cost-effective way. They encompass all development phases: from design to marketing. Key resources are the physical, intellectual, financial and human inputs required to trigger activities and ultimately deliver the value proposition. They respond to a logic of business sustainability: a careful planning is required to ensure they will not be depleted before the completion of the set of activities.

Customer segments entail different groups of actors potentially interested in climate services’ value proposition. Each cluster may have separate needs: the market segmentation supports their characterisation and defines priorities. Groups are separate if they react differently to the value generated by the service, if they use different channels to interact with the service providers and even if they are willing to pay different prices. The dichotomy between mass and niche markets is an example of this heterogeneity. Relationships, as much as customer segments, are also highly differentiated and adapted to the needs of target users. They may be fully automated or personal and they support the client acquisition, development and scaling-up phases of every climate service. Relationships entail the way users live the experience and engage with the provider. Examples of this block are provided by personal assistance features, learning opportunities and value co-creation process. Channels are the tools any service uses to communicate with and relate to its segments. They may work on- and off-line through in-house or outsourced infrastructures. Channels raise awareness about the service’s mission and values; they support the evaluation of the activities offered and they guide customers through the purchase steps.

Each member of the value network may offer tangible (priced products, components or services) and/or intangible values. While the tangible values are actual exchanges between partners and they normally involve Memorandum of Understandings (MoUs), contracts, invoices and requests for proposals, the set of intangible values can be further sub-categorised in knowledge and benefits. While knowledge includes information, competences and skills, benefits comprise reputation factors and prestige. The value network analysis is a mandatory step when dealing with the customer segment: the set of the target users and interested stakeholders shape the activities required to deliver the value proposition and provides boundary conditions to the available resources [38].

3. Materials and methods

3.1. The theoretical framework: the Grounded Theory method

Qualitative analysis is a scientific method of observation of properties and patterns using non-numerical data [45]. Qualitative market studies [46,47] typically employs focus groups, expert surveys and interviews. here, we use a cross-case approach [48] to uncover emerging patterns across different climate services typologies (cases).

Using the Grounded Theory Method [49], researchers collect, store and analyse data that will be used as building blocks of a theory. The interview technique is one of the possible tools used to observe a phenomenon. An interview is “an interchange in which one person… attempts to elicit information or expressions of opinion or belief from another person or persons” [50]. The process of interviewing generates mutual learning between those involved and creates primary data that can be then analysed and interpreted [51]. In order for interviews to be effectively used, some key steps must be followed, crucially split in three classes: design, data collection and data analysis. A clear identification of the research question creates the conditions to understand if and how interviews are the most appropriate tool to solve the problem. Structured interviews follow a predetermined script, that cannot be adapted to different actors or situations. Conversely, unstructured interviews are based on the answers of the respondents. Questions are spontaneous and are shaped by the direction the discussion. In semi-structured interviews the interviewer asks a pre-defined set of questions but is also free to ask more and more in-depth depending on the direction of the conversation. The elaboration of an initial set of questions serves as basis to further proceed in the grounded theory method. This represents an initial attempt to frame the problem and may not be exhaustive: revisions and edits are often required.

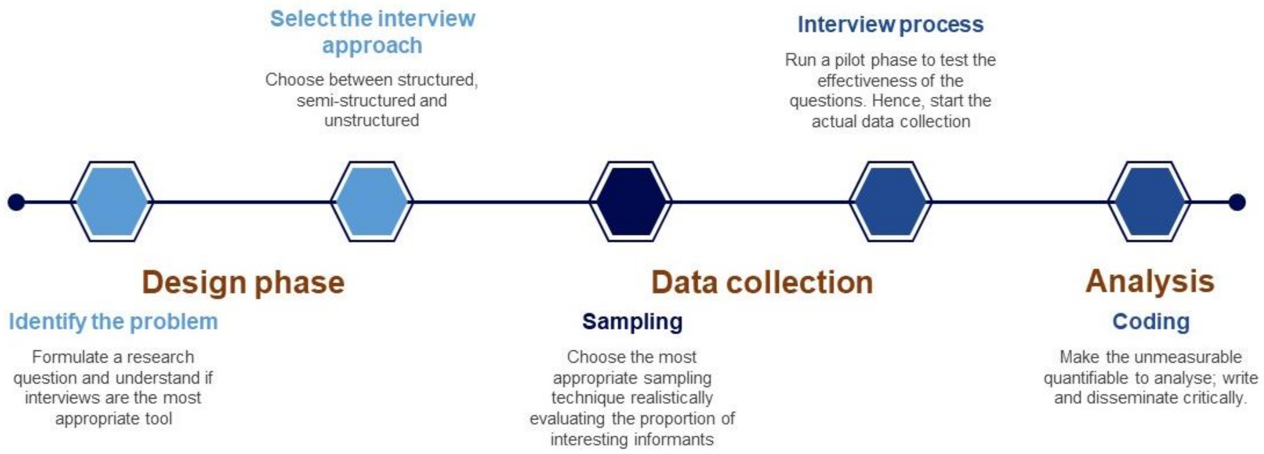


Figure 19 | The key steps of an interview process

Data collection starts with identification of a sample of interviewees. A range of sampling strategies exist, including (i) snowball, that uses initially identified informants to contact relevant others; (ii) representative sampling, where the number of selected participants are representative of the total population; (iii) random sampling, where selected informants are interviewed randomly [52]. Pilot interviews should ideally refine and test the effectiveness of the questions. Analysis of interviews involves “coding”, that is placing “tags or labels for assigning units of meaning to the descriptive or inferential information compiled during a study” [53]. Coding allows the classification of pieces of data and transformation of non-numerical to numerical data. Codes might have been previously set, which is the typical case for structured interviews, or may instead be chosen using an “open coding” procedure. Codes are units organized in “concepts”, which are regroupings of the available data to reach more analytical conclusions. Throughout the coding procedure, memoing is essential [54]: the act of writing memos and notes related to (i) codes; (ii) the theory behind the process; and (iii) all relevant methodological issues. The so-collected reflections enrich the analysis and support the writing phase.

Interviews include some subjective considerations before, during and after data collection [54,55]. The choices the researcher makes can affect the outcomes of the process. However, the cross-case grounded theory method allows for identification of emerging patterns that can be very useful for exploratory research.

3.2.Sampling climate services provision

Given the heterogeneity of definitions, typologies and contexts, a comprehensive catalogue of climate services is not available. Besides, climate services are developing by a wide variety of public and private actors that implement research and innovation actions, as well as for-profit commercial activities differently. Research institutes are involved in the provision of climate innovations: they are rarely working under for-profit logics, but create value for society as a whole. Therefore, the application of a business framework to these entities may be controversial [40].

Public actors (such as meteorological organisations and research performing institutes) were the first to value the climatic information and to extend their services beyond pure weather applications [56]. However, a range of incumbent players is widening the spectrum of available activities and actions. This variety has implications on the business model they use to perform their activities. To allow a more precise identification of the building blocks of business model for climate services, we first distinguished between three forms of climate services discriminating the funding source of their activities: (i) Ongoing publicly-funded projects; (ii) Completed projects; (iii) Private firms.

For (i) and (ii), I focus on European projects operating in a twelve-year period (2005-2017) and funded under different strategic programs managed by the European Commission. I consult the

Community Research and Development Information Service (CORDIS) platform and I launch multiple queries using a combination of keywords[9] under any program, domain and country[10]. The choice of keywords potentially affects the sample included in the research. In particular, hydro-meteorological and weather services may respond to the set of fundamental characteristics climate services have. Despite this limitation, the institutionalized keywords as they are shared by the three most relevant frameworks at European and global level: the definition of climate services [1], the Global Framework for Climate Services [57] and the European Roadmap for Climate Services [58].

The query in CORDIS reported 153 results. I restrict the interest to programs dedicated to the development of an actual service or application. This includes practical, open-access tools and innovations, platforms, training activities aimed at increasing public and private stakeholders' engagement in this type of services. No individual grants (e.g.: Marie Skłodowska-Curie Research Fellowship Programmes) are included and purely theoretical initiatives. Additionally, two other major information sources are surveyed: the Copernicus Climate Change Service (C3S) and the Climate-ADAPT database. Regarding the former, I focus on the section dedicated to "providers", while for the latter, I use "climate service" as key word to perform the research. Successively scientific managers of identified initiatives are contacted and interviewed. I use the same interview protocol to interview 14 climate services developed in the context of the European funded project CLARA ("Climate forecast enabled knowledge services"). I conduct additional 22 interviews: 14 ongoing publicly-funded climate service provisions and 8 completed projects.

For the private firms a snowball sampling technique was used. I ask the Scientific Managers of each publicly-funded initiative included in the sample to mention private entities working on climate services or providing any form of climate service. This non-probability sampling technique presents some limitations: (i) it does not pretend to be representative of the population of interest; and (ii) it may suffer of a selection bias. However, managers interviewed are experts in the field and their judgement allowed us to reach innovative for-profit actions. Overall, I conduct 32 interviews.

3.3. The interview process

Interviews were conducted – whenever possible – as in-person discussion, by telephone otherwise. The interview lasted approximately one hour.

I first presented the objectives of our research and fostered a shared understanding of what climate services are. Then, I explained the framework used to collect and analyse the interviews: the Business

[9] "climate services" AND "Climate Services" AND "Climate Service*"
[10] The query was performed in March 2017

Model Canvas. Finally, I asked the interviewees to highlight the main barriers and potential opportunities in the design, development and eventual launch of the service. Therefore, this chapter works with a reviewed version of the standard BMC, which presents two additional sections that span across the different building blocks. The first looks at "Opportunities", while the second deals with "Barriers". The revised version of the BMC (Figure 20) puts emphasis on the bottlenecks and gains that climate service provision generates. The two aspects are particularly relevant in the context of disruptive products because they identify where gaps are and try to foresee potential concerns.

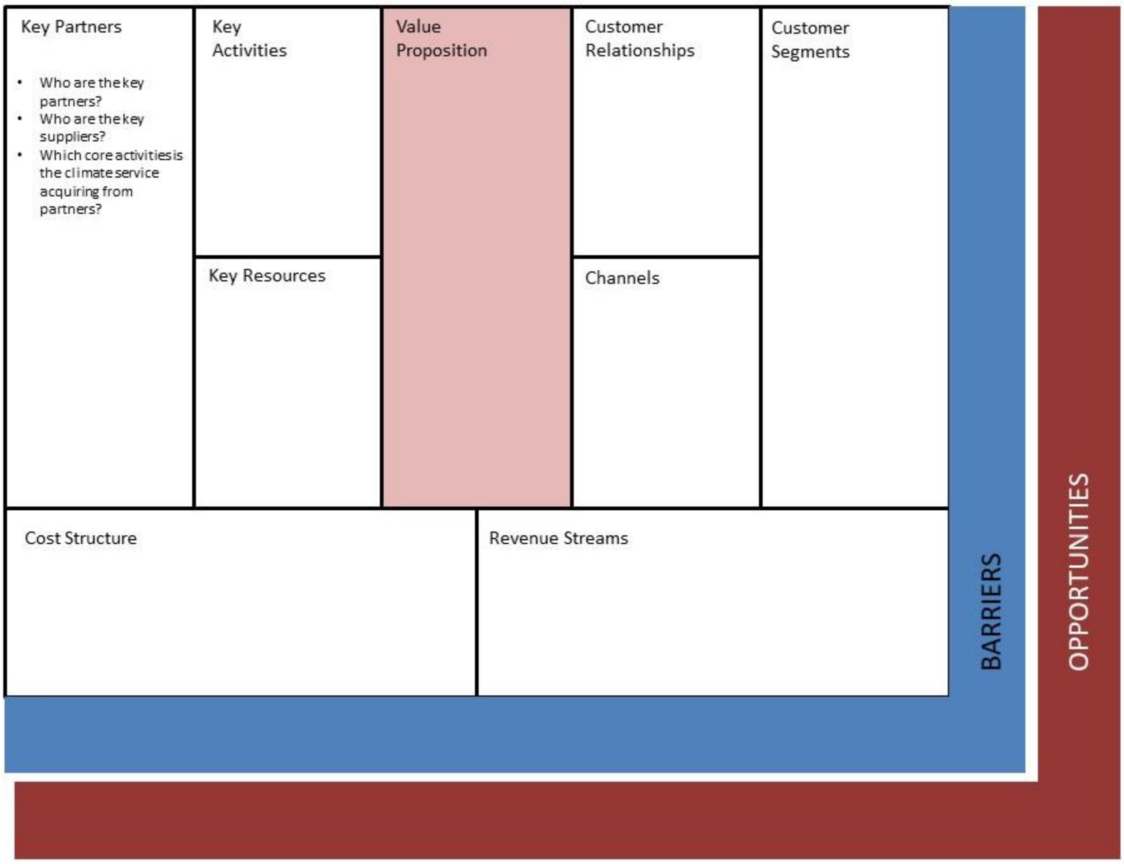


Figure 20 | Extended Business Model Canvas

Interviews includes a pre-determined protocol of 17 questions (see Supplementary Material, chapter 4), leaving freedom to deepen some aspects of the conversation. The order of the questions was not pre-defined on purpose: the interviewee was left free to jump from one topic to another autonomously. This flexibility provides the core methodological input for a linguistic and content analysis. In fact, it is not just the content that matters, but also the order in which an informant mentions key concepts. The process of building a narrative clarifies and complements the talk. Furthermore, it supports qualitative and critical reflections. Hence, the pre-defined set of questions has to be perceived as a roadmap, a protocol that facilitates the allocation of questions, rather than the identification of answers.

3.4. A quali-quantitative approach

Codes and labels are the building bricks of a quali-quantitative approach: in this chapter, I combine content analysis with network analysis to visualise, analyse and interpret the outcome of the interview process. Content analysis responds to the need of systematically analysing bodies of texts, visuals and matters, without including personal judgements and perspectives (Krippendorff, 2004). It allows the identification of patterns throughout the text by transforming qualitative information into quantitative ones. It uses labels and codes to perform statistical evaluations using textual information. Outputs of this approach comprise word frequencies and descriptive statistics of the interviews' recording under study. By treating words as data gives researchers the freedom to quantitatively assess the latent and manifest meanings in the text [60].

Content analysis can also uncover the relationships between different tokens of texts and codes. However, it is not sufficient per sé to describe the properties of these networks. That is why I complement our methodological framework with Network Analysis [61], capable of detecting and characterising links between individual nodes to derive generally valid considerations about a group of agents [62]. Networks (N) are constituted by vertices – or nodes, V(N) linked together by edges – or links, E(N). Whenever the direction of the relationship between two nodes matter, networks are represented as directed or undirected graphs [63]. Networks analysis supports both the visualisation and analysis of textual information, by efficiently representing the links between concepts and by computing statistical evaluations through centrality analysis. Analysis of networks' characteristics provides an insightful overview of the general features of the environment in which nodes move. Furthermore, the study of nodes highlights the influential poles of action, uncovering where central, neutral or marginal actors stay in a quantitative way. The computation of centrality measures is important to understand the role of certain vertices in driving and spreading information efficiently.

I assign codes to portions of text (tokens) through an open coding procedure. I then iteratively proceed through axial coding, a technique that involves a regrouping of the data to move from simple codes to more analytic concepts [54]. Concepts are grouped in code categories, that represent a component of the revised Business Model Canvas. Codes are then used to build a graph and to explore the complexity of the storyline and ultimately of the business model of each initiative in the sample. Networks were constructed in R and exported in Gephi: an open-access network visualisation software.

The 32 interviews form a directed network of 70 nodes (the codes) and 1892 weighted links. The direction of the links is provided by the order in which project managers presented their narrative around their business model. Edges of the network are weighted according to the frequency of the connection between the two codes. This approach builds upon a consideration around the way informants structure their narrative: the chronological location of codes matters in the formation of the directed graph, as well as the proximity of two codes throughout the text. This is allowed by the use of semi-structured interviews that gave freedom during the conversation to jump from one topic to another without losing focus on the core script. This approach [64] allows to retrieve information on how certain codes relate to each other within a token. It has been proved successful in education empirical research [65] and in theoretical works [66,67]. Hence, the network of codes becomes a map defined both across time and space that describes not just the content, but also the relationship between different concepts, as provided by the informant. When building our network, we mixed the proximity approach [68] with the chronological order of appearance of concepts throughout the interview [69], allowing for non-mutually exclusive codes to interact in a directed, weighted graph. Given that two codes may actually overlap, the relationship between them can be either bidirectional (if they are overlapping) or unidirectional otherwise. The isolation of a given node implies that the token of text deals with a single topic, expressed by a node.

Descriptive statistics at network and node level are computed to uncover the structural properties of the graph and to quantitatively assess the relationships between the different Business Model Canvas sections. Network analysis provides insightful information and complements the content analysis because it looks at central codes relating them to the others and within their network. Concepts are not central per sé, but only when and if they are related to others. Therefore, the role of relationships acquires significance and moves the analysis further both methodologically and content-wise. To achieve this goal, I compute the size of the nodes as equivalent to the PageRank centrality. This is an eigenvector-based algorithm. The score assigned to each node can be interpreted as a fraction of the time “spent” on that given node. Despite its wide use in the World Wide Web domain, PageRank is a suitable centrality measures for networks derived from textual material because high values of PageRank can be due either to (i) multiple codes (other nodes) pointing at the one under scrutiny or (ii) some highly relevant codes pointing at the target one. Once ranked nodes according to their PageRank score, I restrict our analysis to the network’s giant component. I use the giant component to extract and interpret considerations around the business model used.

4. Results and Discussion

Results from the content analysis provide insights on the use and spread of codes across and within interviews. Outcomes of the coding procedure are related to the frequency of specific concepts, which highlight where topics of interest are, rank them and set the grounds for cross-case comparisons. Furthermore, the analysis of the content of the interviews reveals what has not being mentioned.

Topics that are often disregarded can be as relevant as mentioned ones.

The relationship between frequency of mention and the number of interviews is quasi-linear (Figure 21). Therefore, some key concepts seem to be familiar to every type of climate service provision analysed, independently on their public or private nature. When looking at the frequency distribution of codes, the most cited ones belong to the domain of the value network, followed by the value proposition (Figure 22). Marketing and business-related activities are mostly disregarded (<5 mentions), while technical aspects behind the service are stressed by 87.5% of the interviews. Within the domain of value proposition, the top cited codes are related to the provision of information about energy production and use. Climate services are also useful to estimate the costs and revenues generated. They use forecasts and climate projections and solid research-grounded products.

Project managers interviewed used the widest portion of their time to cover the requirements of the development phase. Due to the innovation characteristic of climate services, the technical improvements at both methodological and operational level are crucial. The lack of attention to the financials behind the service is an alarming signal and is worth discussing. Ongoing projects tend to consider the Cost and Revenue Stream as a secondary step in their activities (Figure 23). This is mostly due to the nature of funding they receive from European or national bodies. However, considerations around the economic feasibility of the service are essential to launch the product on the market. Potential clients and targeted users may have different willingness to pay and may alter the financial planning if not carefully prepared in advance.

Within the value network, I explore the most frequent terms differentiating by code category. Climate service provision is perceived as a tool to generate innovation throughout the value network and to boost internal processes, ultimately increasing productivity and effectiveness. Client and stakeholder management is pursued through online (web-based infrastructure) and offline (workshops/conference/seminars and direct contact) interactions. Key activities are delivered via non-competitive alliances or joint ventures between different economic actors. Climate services provision is mostly targeting public entities and policy makers: tailor-made products exploit the in-house knowledge and expertise to provide seasonal forecasts, modelling products and often impact assessments. The qualitative assessment of the interviews reveals that in-house competences and experience are key resources that a consortium of different partners can pool together. Seasonal forecasts, model and research efforts dominate the key activities component of the Business Model, while the identified users are equally shared between private and public actors and they are engaged through a co-generation approach to co-develop a “user-friendly” service.

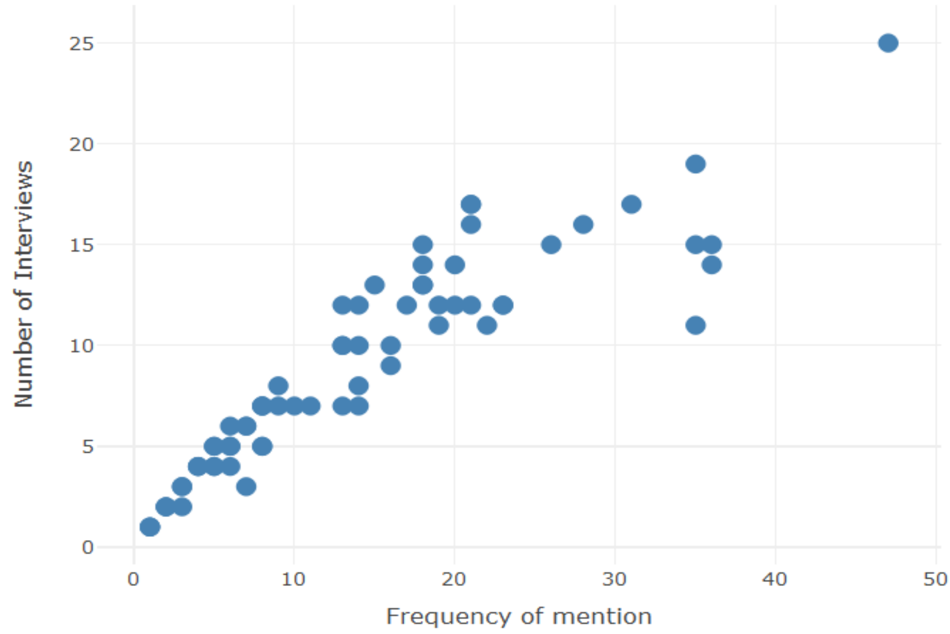


Figure 21 | Frequency of codes vs Number of interviews

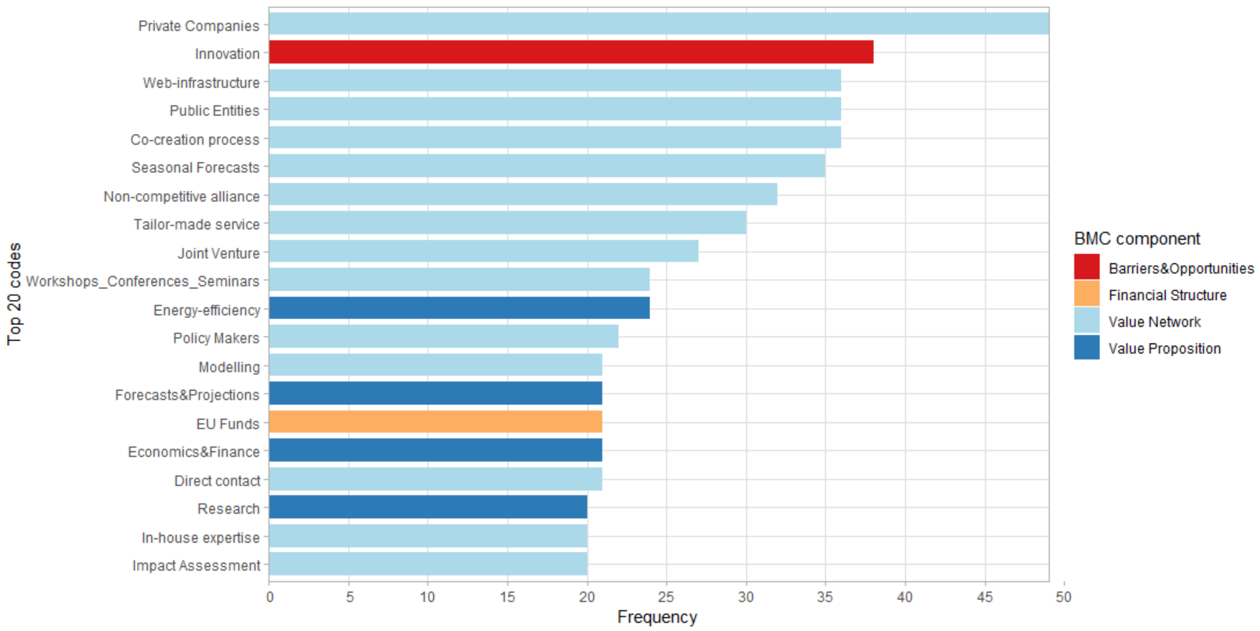


Figure 22 | Most cited codes across interviews

To understand the circumstances in which the value network plays a crucial role, I further detailed the analysis discriminating between typology of projects (Figure 21). As expected, the role of partners and stakeholders in providing the adequate resources to perform key business activities is what matters once the service reaches the final prototype stage ("The interchange with other projects has been crucial throughout the duration of the activities and provided mutual learning opportunities while developing the service”[11]). Instead, given their work in progress activities, ongoing projects extensively use their interview time to cover topics related to the value proposition (“The aim of the service is to provide users with the opportunity to assess the impacts of future planning scenarios on local urban air pollution levels”[12]). The punctual definition of the value proposition is a core aspect of success in the case of every innovation [38]. It provides a careful estimation of the needs, approaches, benefits and competition requirements (NABC) the service provider faces [70].

The NABC Framework helps the climate service provider to consider the value proposition by working systematically with the four elements and to identify where competitive advantages lie. A need is related to an important and user-specific issue and can be solved through a disruptive and efficient approach. This should result in the generation of benefits from the customer’s perspective. These may range from lower costs to higher performance or decreased risks and must be higher than the ones offered by the competitors. In the design and development phases these considerations must be addressed as preliminary and continuous exercise to overcome barriers and identify opportunities. The definition of a clear value proposition also helps to identify a customer segment, which should be identifiable, reachable, but also stable to ensure sustainability of the planned activities [38].

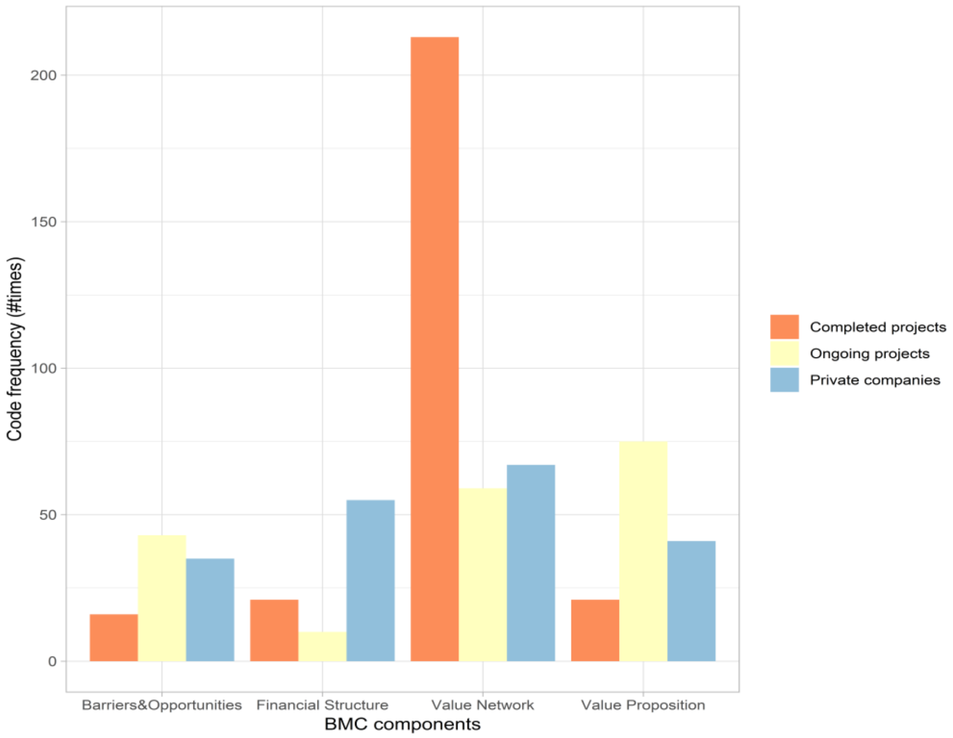


Figure 23 | Most cited BMC components per type of climate services

I first compute network-based descriptive statistics at graph level [63]. Measures of network topology also support the general understanding of network’s contents [71]. The number of nodes and links gives

[11] Extracted from CLIMRUN

[12] Extracted from the AirCloud service – CLARA project

the size of a network, together with the average path length and the density. The former depends on the network size and provides a measure of the number of edges included in the mean path [72,73]. It ranges from 0 (minimum value) and the diameter (the maximum possible distance-based value). The network's diameter takes value 2, while the average path length is 1.1809. Low values of average path length describe highly interconnected graph. Some codes are strongly interrelated: connections happen especially within the value network and mainly link key activities and key resources with customer segments and key partners. Across code categories, features of the value proposition are mainly paired with value network's ones. Among the topological metrics, I also compute the density, which provides an indication of the degree of completeness of a graph and can take values between 0 (fully incomplete) and 1 (theoretically complete). The network has a density of 0.415, which implies that slightly less than half nodes are connected. This finding is not surprising given that nodes are text-derived codes and not individual agents (e.g. people or organisation). However, the connectedness of more than 40 percent of the total available codes is enough to highlight that some concepts are strictly related to each other.

Once computed the network statistics, I characterise individual nodes. The average degree indicates the mean number of links touching a given node. In this case, this is equivalent to 27.82. This metrics provides an innovative visualisation of already existing outputs from the content analysis. However, for directed graphs, we can differentiate between in-degree and out-degree node-level metrics. These provide the quantification of – respectively – the links directed towards and outwards a given node (related figures in Supplementary Material, chapter 4). Outcomes of these representations provide insightful information about the temporal mapping of the concepts throughout the interviews: the most cited codes (normally included in the value network and interesting key activities) acquire relevance in a second moment and they are mentioned after considerations about the value proposition and the barriers encountered to deliver it. Therefore, by following the direction of the relationship, we could assess the chronological order in which concepts were presented by informants. Nodes' colors (Figure 24) are given by the different Business Model Canvas sections and help visualising the linkages between them, moving towards a comprehensive understanding of the interviews' dynamics.

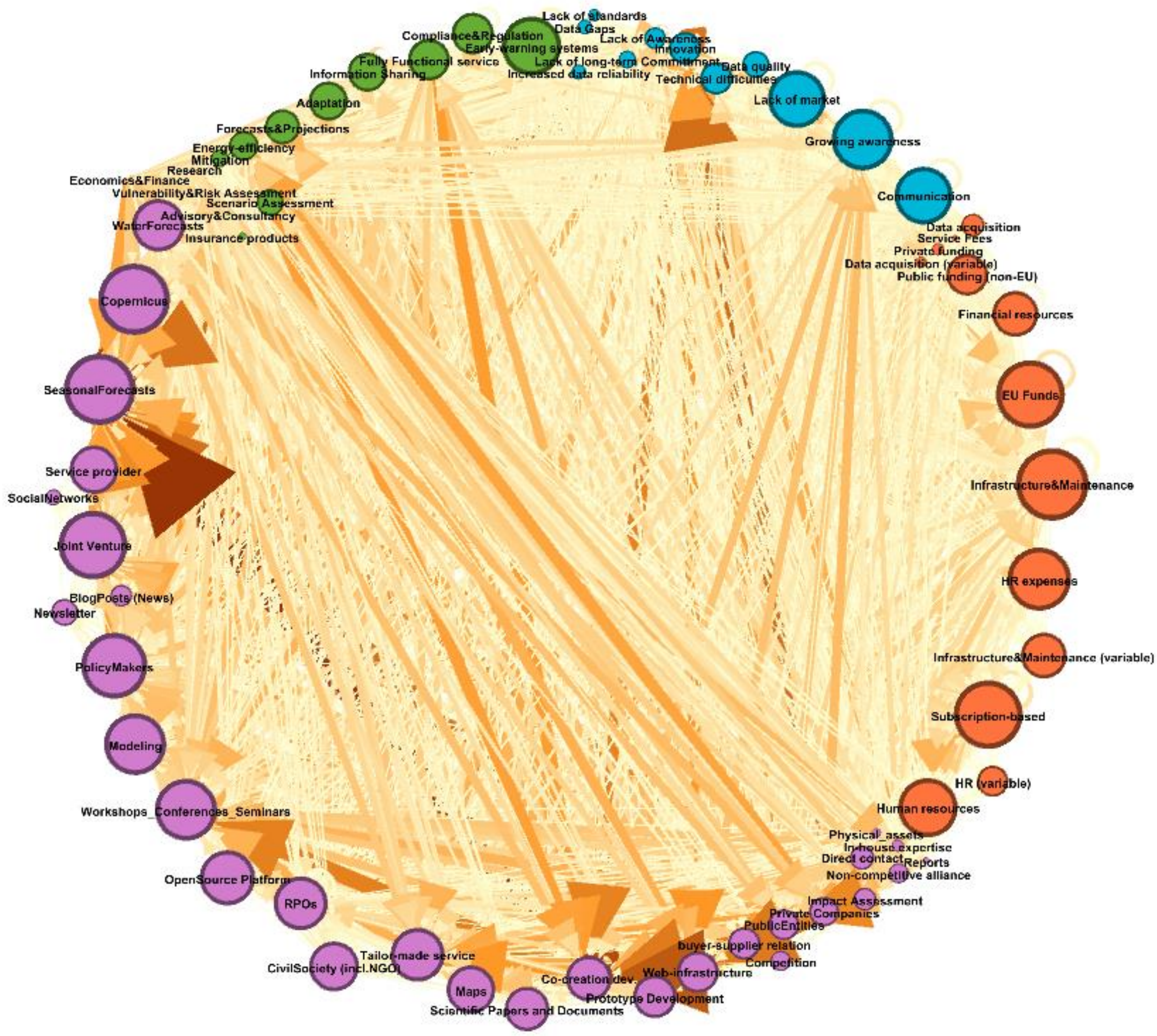


Figure 24 | The network of codes

PageRank centrality is computed to understand the importance of the codes moving beyond the findings of content analysis (Figure 24). Codes are ranked on their PageRank score: the most relevant ones are such both because they are highly mentioned and because they receive inputs and send outputs to other significant nodes. Copernicus, Water Forecasts, Seasonal Forecasts and Early-Warning System are the top ones. The analysis is restricted to the network's giant component where Seasonal Forecasts is the ultimate node of the connected portion (Figure 25). There exists a tight and strong link between some key concepts: "Co-creation development", "Seasonal Forecasts", "Tailor-made service” and “Web-infrastructure”, which are also frequently mentioned in the same token. Based on the direction of this relationship, some useful implications about the role of co-creation can be made: it directly serves as tool to generate the forecasts together with stakeholders and partners, but it is also used as mean for tailor-made final services. Approximately half of the network is connected through the “Co-creation development”: 45.58% of the overall edges are pointing towards the node. Interestingly, innovation is conceived as an opportunity and is achieved by both private and public agents. It is tightly connected to energy-efficient technologies, as well as to the provision of forecasts and climate projections. It interests the co-creation process and supports information sharing activities both offline (Workshops/Conference/Seminars) and online (Web-based infrastructure).

Our quali-quantitative methodology provides insightful information on the business model some of these climate services provision use (Figure 26). On average, climate services included in the sample are mostly working online and use a subscription-based mechanism (e-business model): they supply a constant flow of information and data under the payment of a fixed amount of money, on top of the installation costs. The network analysis also highlighted the most interesting sector of operation: Energy, Water and Disaster Risk Reduction. The web platform is used extensively for seasonal forecasts: both the direction and the thickness of the edge between the two nodes provides an indication of the high frequency of mention within the same piece of narrative. Given the high degree of operability, these services are suitable for both public and private actors, provided that they are tailor-made. Copernicus appears as a central node of the code network and is directly linked within the e-business model structure. This is not surprising: the launch of the Copernicus Climate Change Service (C3S) and the Climate Data Store offered the free access to data and post-processed information, which would have otherwise been difficult to process and use.

The e-business model described by our sample deserves a reflection on the financial sustainability. As by Figure 26, fixed and variable costs associated with the development of the service are “Infrastructure and Maintenance”. These may require a significant initial investment, depending on what is already available in-house. However, the competences of the consortium of partners – when existent – are key resources capable of lowering the instalment expenses. As highlighted during the interview process, in-house competences are enhanced and increased by the exposure to other organisations’ expertise (“We combined the models and tools we have been developed in the past years with the data and expertise of our users. Within the consortium we were first exposed to marketing needs and business models. This new knowledge provides us a fresh look on how we could use the in-house resources. The effects of the merge will be long-lasting: we developed new protocols that we intend to apply in the future"[13]). Furthermore, the co-creation process supported a shift towards new actors ("Since the moment we started developing the new indices, we understood there was a massive market potential for these products working hand.in-hand with cutting-edge research organisation, who support the development and back-up the design of these innovations"[14]).

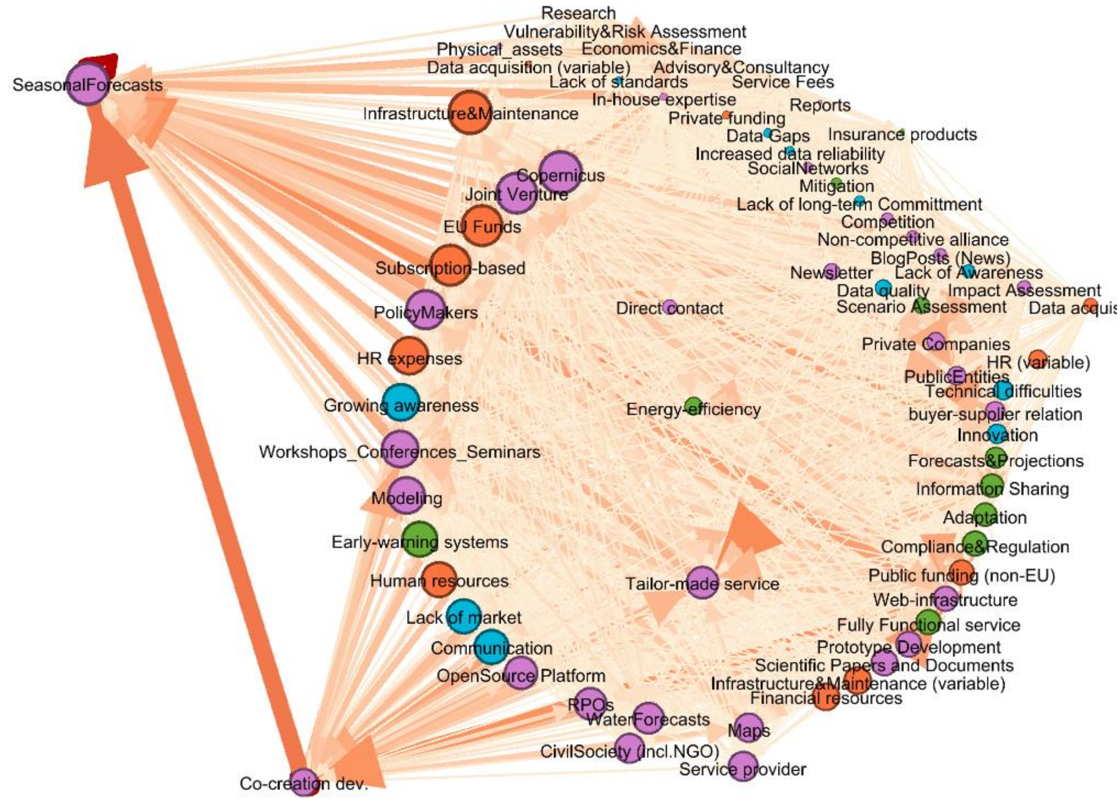
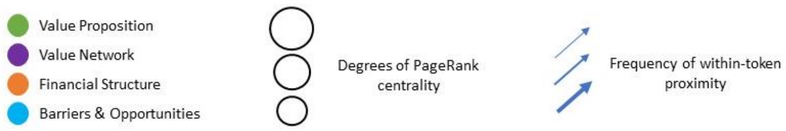


Figure 25 | The giant component



[13] Extracted from the interview with WRI
[14] Extracted from the interview with Amundi

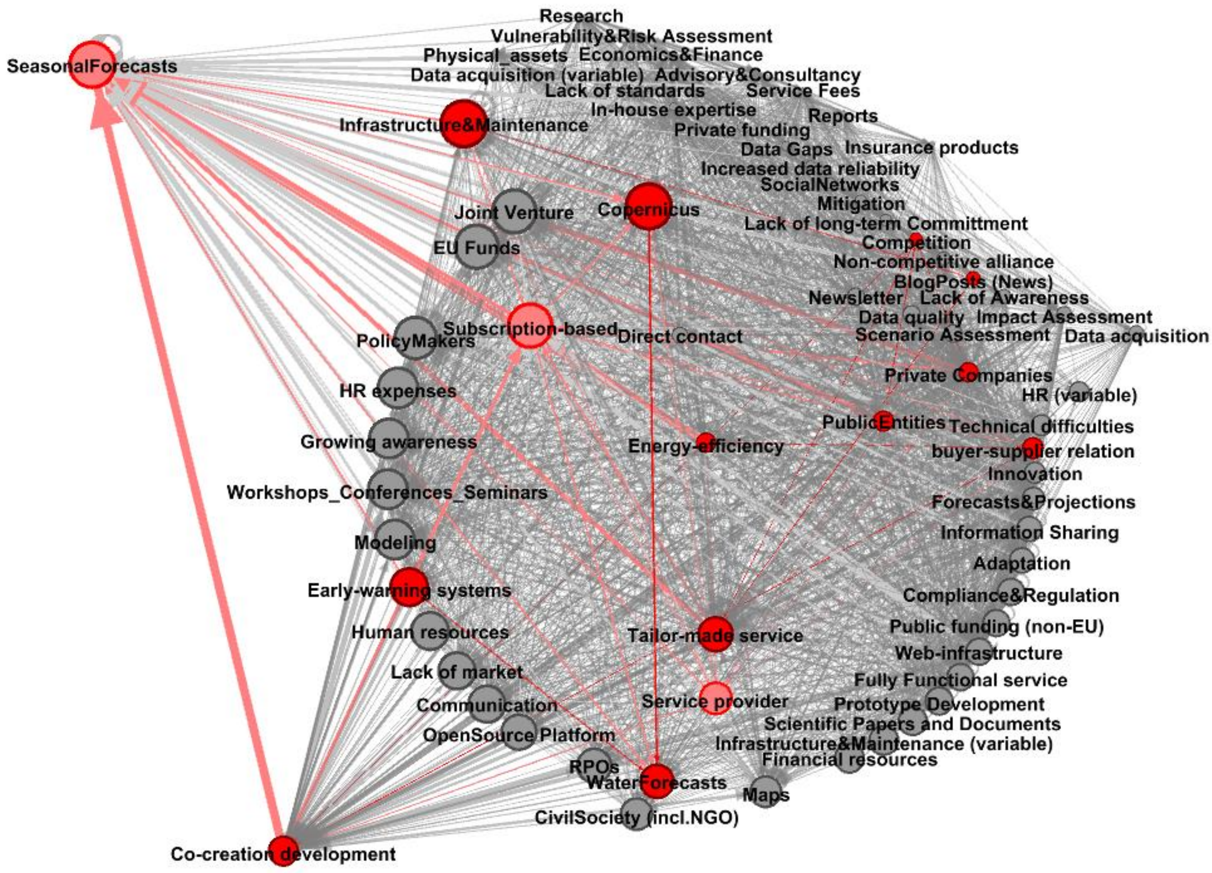


Figure 26 | A subscription-based business model

5. Conclusions

Theoretical and empirical investigation of business models for climate services is important for fostering services' adoption and boosting the market for climate innovation. Business models are firm-specific strategic choices aimed at creating and retaining value for a target user. Therefore, they provide a roadmap that guides the collection, use and dissemination of resources to impact on a specific set of users. In the case of climate services, appropriate business models may act as market signals and provide the most adequate means to overcome future and potential barriers.

This chapter uses semi-structured interviews with 32 climate services providers in Europe. The sample of interest is constituted by private firms, consortia members of past and ongoing projects funded under different research and innovation programmes. The semi-structured interviews were guided by a set of predefined questions but service developers were left to unfold their own narratives. The Business Model Canvas is used to frame the analysis and split the text corpus into nine components, grouped in three macro categories: Value Proposition, Value Network and Financial Structure. The standard BMC has been revised to consider one additional macro category that includes barriers climate services face and opportunities they may want to exploit. A quali-quantitative approach is used to (i) analyse the content of the narrative (content analysis) and (ii) to assess the role of different concepts in shaping the set of strategic choices managers have been and are doing (network analysis). The paper from which this chapter is derived represents one of the first attempts to explore business models for climate services. Despite the wide contribution of public funding (at European, national and regional level), private actors are those concerned with the financial structure. This highlights a certain lack of sustainability in climate services provision and a relatively short-looking attitude towards the delivery of climate information. Consequences of such a negligence may be relevant when it comes to the sustainability of projects about climate services: a careful business plan is required to support the research phase. Efforts toward this direction have been made: multiple public funding schemes (such as the European Horizon2020) are now stressing the importance of a business logic when applied to new forms of climate innovations.

In this chapter I find that, among the components of the BMC, the Value Network receives the majority of attention. This includes not just the Customer segment targeted and the Channels used, but also the range of stakeholders involved in every phase of climate services provision. The creation of consortia of partners is essential to enhance the existing in-house resources and to foster innovation: by pooling together competences and expertise, agents can fill their gaps and engage in a mutual learning process. This holds for both research-dominated components (such as modelling and framework creations), as well as for business-related aspects (*e.g.* marketing and budgeting). Boosting these forms of exchange is key to design, create and spread climate innovation. Interestingly enough, the Value Network plays a significant role for both projects and private firms (Figure 23).

The quali-quantitative approach exploited both content analysis to extract information about the most mentioned concepts and network analysis to provide insights on the links between different codes. By integrating methodological proposal from theoretical [68,74] and empirical [69] research, this chapter offers an innovative approach to analyse qualitative textual information. A chronologically-consistent map of codes is created based on the way codes appear in the transcription of the interviews. Codes formed a directed weighted graph of 70 nodes and 1892 connections. The size of each node was attached to their PageRank score, a measure that builds upon the importance of the code itself and their direct neighbours. Relationships, rather than simple frequency of mention, acquired significance and offers new insights to the content analysis.

Results include a tight and direct connection between some crucial concepts. The direction of these relationships provides the opportunity for some policy-relevant and business-related considerations: (i) the role of co-creation in supporting climate services is directly impacting on the generation of seasonal forecasts (by connecting partners within the same consortium), but it also serves as mean to deliver tailor-made final services. Results are widely driven by the sample composition, but climate services projects connected to seasonal forecasts still constitute less than half of the overall interviewees, while findings are strongly indicating the dominance of co-development. On average, climate services provision is mostly working online through a subscription-based mechanism. This holds particularly for Energy, Water and Disaster Risk Reduction domains and it is a crucial resource when delivering seasonal forecasts. A tailor-made online platform is found to be suitable for both public and private actors, through the direct communication between service provider and target user. In this sense, business models can serve as enablers to overcome barriers and identify opportunities.

The chapter has some crucial limitations that leave room for future research. The sample used for this work did not aim at being representative of the population of climate services providers. This is due to a lack of a comprehensive and detailed database of climate services operating in Europe. The sample of climate services provision has the potentiality to alter the results and to drive conclusions. Nonetheless, the chapter does not aim at offering a universally valid characterisation of business models for climate services, but rather some explorative insights to stimulate the debate around this topic. Second, to perform the content analysis an "open coding" procedure is employed. This is justified in the case of explorative research but builds upon a subjective judgement that the coder has to take. This open remark may be solved through the consultation of experts in the field, who can revise the chosen codes and suggest alternatives. It is worth mentioning that a certain discretion will always be part of qualitative methodologies, especially in presence of small samples. Finally, the use of network analysis is based on the way codes were linked. The methodology has been adapted from insights provided by recent literature [68,69,71,74]. However, it requires further validations and additional checks to reach robustness.

References

1. Barron, E. J. A climate services vision: First steps toward the future. *Board on Atmospheric Sciences and Climate* (2001).
2. Bruno Soares, M., Alexander, M. & Dessai, S. Sectoral use of climate information in Europe: A synoptic overview. *Climate Services* (2017) doi:10.1016/j.cliser.2017.06.001.
3. Bruno Soares, M. & Dessai, S. Barriers and enablers to the use of seasonal climate forecasts amongst organisations in Europe. *Climatic Change* **137**, 89–103 (2016).
4. Vaughan, C. & Hewitt, C. Surveying Climate Services: What Can We Learn from a Bird's-Eye View? *American Meteorological Society* (2018) doi:10.1175/WCAS-D-17-0030.1.
5. Brasseur, G. P. & Gallardo, L. Climate services: Lessons learned and future prospects. *Earth's Future* **4**, 79–89 (2016).
6. Barr, S. H., Baker, T., Markham, S. K. & Kingon, A. I. Bridging the Valley of Death: Lessons Learned From 14 Years of Commercialization of Technology Education. *Academy of Management Learning & Education* **8**, 370–388 (2009).
7. Buontempo, C. *et al.* What have we learnt from EUPORIAS climate service prototypes? (2017) doi:10.1016/j.cliser.2017.06.003.
8. Soares, M. B., Daly, M. & Dessai, S. Assessing the value of seasonal climate forecasts for decision-making: *Wiley WIREs Climate Change* (2018) doi:10.1002/wcc.523.
9. Brasseur, G. P. & Gallardo, L. Climate services: Lessons learned and future prospects. *Earth's Future* **4**, 79–89 (2016).
10. Boons, F. & Lüdeke-Freund, F. Business models for sustainable innovation: State-of-the-art and steps towards a research agenda. *Journal of Cleaner Production* **45**, 9–19 (2013).
11. Chesbrough, H. Business Model Innovation: Opportunities and Barriers. *Long Range Planning* **43**, 354–363.
12. Hansen, E. G., Grosse-Dunker, F. & Reichwald, R. SUSTAINABILITY INNOVATION CUBE — A FRAMEWORK TO EVALUATE SUSTAINABILITY-ORIENTED INNOVATIONS. *International Journal of Innovation Management* **13**, 683–713 (2009).
13. Long, T. B., Blok, V. & Poldner, K. Business models for maximising the diffusion of technological innovations for climate-smart agriculture. *International Food and Agribusiness Management Review* **20**, 5–23 (2017).
14. Doganova, L. & Eyquem-Renault, M. What do business models do? *Research Policy* **38**, 1559–1570 (2009).
15. Shafer, S. M., Smith, H. J. & Linder, J. C. The power of business models. *Business Horizons* **48**, 199–207 (2005).
16. Vaughan, C., Buja, L., Kruczkiewicz, A. & Goddard, L. Identifying research priorities to advance climate services. *Climate Services* **4**, 65–74 (2016).
17. Wirtz, B. W. Business Model Management.
18. Tikkanen, H., Lamberg, J., Parvinen, P. & Kallunki, J. Managerial cognition, action and the business model of the firm. *Management Decision* **43**, 789–809 (2005).
19. Casadesus-Masanell, R. & Ricart, J. E. From Strategy to Business Models and onto Tactics. (2010) doi:10.1016/j.lrp.2010.01.004.
20. Falloon, P., Fereday, D., Stringer, N., Williams, K. & Gornall J, et al. *Assessing Skill for Impacts in Seasonal to Decadal Climate Forecasts*. *Journal of Geology & Geosciences* vol. 2 1–4 (OMICS International., 2013).
21. Schilling, M. A. *Strategic management of technological innovation*. (2008).
22. Brasseur, G. P. & Gallardo, L. Earth ' s Future Climate services : Lessons learned and future prospects. *Earth's Future* 79–81 (2016) doi:10.1002/2015EF000338.Received.
23. Larosa, F. & Perrels, A. *ASSESSMENT OF THE EXISTING RESOURCING AND QUALITY ASSURANCE OF CURRENT CLIMATE SERVICES Grant agreement 730500 EU-MACS*

European Market for Climate Services Deliverable 1.2. (2017).
24. Larson, B. A. *Sustainable development research advances*. (Nova Science Publishers, 2007).
25. Brenner, T., Capasso, M., Duschl, M., Frenken, K. & Treibich, T. Causal relations between knowledge-intensive business services and regional employment growth. *Regional Studies* (2017) doi:10.1080/00343404.2016.1265104.
26. Strambach, S. Innovation Processes and the Role of Knowledge-Intensive Business Services (KIBS). in *Innovation Networks: Concepts, Challenges in the European Perspective* (eds. Koschatzky, Knut., Kulicke, Marianne. & Zenker, Andrea.) (Physica-Verlag HD, 2001). doi:10.1007/978-3-642-57610-2.
27. Miles, I. *et al.* Knowledge-Intensive Business Services: Users, Carriers and Sources of Innovation. *EIMS Publications* **15**, (1995).
28. Baró, E. The role of knowledge-intensive business services. *Strategies for innovation* 88–97 (2008).
29. Amara, N., Landry, R. & Traoré, N. Managing the protection of innovations in knowledge-intensive business services. *Research Policy* **37**, 1530–1547 (2008).
30. Starbuck, W. H. LEARNING BY KNOWLEDGE-INTENSIVE FIRMS. *Journal of Management Studies* **29**, 713–740 (1992).
31. Xu, X. & Ström, P. The Transformative Roles of Knowledge-Intensive Business Services in Developing Green ICT: Evidence from Gothenburg, Sweden. in *Services and the Green Economy* 99–124 (Palgrave Macmillan UK, 2016). doi:10.1057/978-1-137-52710-3_5.
32. Strambach, S. Innovation Processes and the Role of Knowledge-Intensive Business Services (KIBS). in *Innovation Networks: Concepts, Challenges in the European Perspective* (eds. Koschatzky, Knut., Kulicke, Marianne. & Zenker, Andrea.) (Physica-Verlag HD, 2001). doi:10.1007/978-3-642-57610-2.
33. Flikkema, M., Jansen, P. & Van Der Sluis, L. Identifying Neo-Schumpeterian Innovation in Service Firms: A Conceptual Essay with a Novel Classification. *Economics of Innovation and New Technology* **16**, 541–558 (2007).
34. Service, C. & Commission, E. the European Landscape on Climate Services. (2014).
35. Vaughan, C. & Dessai, S. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* **5**, 587–603 (2014).
36. Medri, S., de Guisasola, E. & Gualdi, S. Overview of the Main International Climate Services. 108 (2012).
37. Cortekar, J. *Review and Analysis of CS Market Conditions*. *EU-MACS Project, Deliverable 1.1* (2017).
38. Osterwalder, A., Pigneur, Y. & Tucci, C. L. Clarifying Business Models: Origins, Present, and Future of the Concept. *Communications of the Association for Information Systems* **16**, 1–25 (2005).
39. Dijkman, R. M., Sprenkels, B., Peeters, T. J. G. & Janssen, A. Business models for the internet of things . *International Journal of Information Management* vol. 35 672–678 (2015).
40. Universalia. Business Models for Research Institutions. *Universalia* (2013).
41. Ching, H. Y. & Fauvel, C. Criticisms, variations and experiences with business model canvas. *International Journal of Small Business and Entrepreneurship Research* **1**, 18–29 (2013).
42. Eppler, M. J., Hoffmann, F. & Bresciani, S. New Business Models Through Collaborative Idea Generation. *International Journal of Innovation Management (ijim)* **15**, 1323–1341 (2011).
43. Allee, V. Reconfiguring the value network. *Journal of Business Strategy* **21**, 36–39 (2000).
44. Clarysse, B., Wright, M., Bruneel, J. & Mahajan, A. Creating Value in Ecosystems: Crossing the chasm between Knowledge and Business Ecosystems. *Research Policy* **43**, 1164–1176

(2014).
45. Babbie, E. *The Basics of Social Research*. (Wadsworth Cengage Learning, 2011).
46. Flick, U. An Introduction To Qualitative Fourth Edition. *SAGE Publications* 506 (2010) doi:978-1-84787-323-1.
47. Seemann, J. Hybrid Insights: Where the Quantitative Meets the Qualitative. *Rotman Magazine* 57–61 (2012) doi:10.1016/S0009-9260(03)00130-2.
48. Miles, M. B. & Huberman, A. M. *Qualitative data analysis : an expanded sourcebook*. (1994).
49. Glaser, B. G. & Strauss, A. L. *The Discovery of Grounded Theory*. (1967).
50. MacCoby, E. & Maccoby, N. The interview: a tool of social science. in *Handbook of social psychology: Theory and Method* vol. 1 449–487 (Reading MA: Addison-Wesley, 1954).
51. Fontana, A. & Frey, J. H. The Art of Science. in *The Handbook of Qualitative Research* (ed. N a Y.L. Denzin) 361–76 (Thousand Oaks: Sage Publications, 1994).
52. Young, J. C. *et al.* A methodological guide to using and reporting on interviews in conservation science research. *Methods in Ecology and Evolution* **9**, 10–19 (2018).
53. Miles, M. B. & Huberman, A. M. *Qualitative data analysis : an expanded sourcebook*. (1994).
54. Babbie, E. *The Basics of Social Research*. (Wadsworth Cengage Learning, 2011).
55. Young, J. C. *et al.* A methodological guide to using and reporting on interviews in conservation science research. *Methods in Ecology and Evolution* **9**, 10–19 (2018).
56. Vaughan, C. & Dessai, S. Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework. *Wiley Interdisciplinary Reviews: Climate Change* **5**, 587–603 (2014).
57. World Meteorological Organisation, W. Climate Knowledge for Action: A Global Framework for Climate Services –. (2009).
58. Directorate-General for Research and Innovation, E. Commission. European roadmap for Climate Services. in (European Commission, 2015).
59. Krippendorff, Klaus. *Content analysis : an introduction to its methodology*. (2004).
60. Pashakhanlou, A. H. Fully integrated content analysis in International Relations. *International Relations* **31**, 447–465 (2017).
61. Otte, E. & Rousseau, R. Social network analysis: a powerful strategy, also for the information sciences. *Journal of Information Science* **28**, 441–453 (2002).
62. Boccaletti, S., Latora, V., Moreno, Y., Chavez, M. & Hwang, D.-U. Complex networks: Structure and dynamics. *Physics Reports* **424**, 175–308 (2006).
63. Otte, E. & Rousseau, R. Social network analysis: a powerful strategy, also for the information sciences. *Journal of Information Science* **28**, 441–453 (2002).
64. Pokorny, J. J. *et al.* Network analysis for the visualization and analysis of qualitative data. *Psychological Methods* **23**, 169–183 (2018).
65. Bodin, M. Mapping university students' epistemic framing of computational physics using network analysis. *Physical Review Special Topics - Physics Education Research* **8**, 010115 (2012).
66. Paranyushkin, D. Visualization of Text's Polysingularity Using Network Analysis Dmitry Paranyushkin Visualization of Text's Polysingularity Using Network Analysis. *Nodus Lab* (2012).
67. Paranyushkin, D. *Identifying the Pathways for Meaning Circulation using Text Network Analysis*. (2011).
68. Paranyushkin, D. *Identifying the Pathways for Meaning Circulation using Text Network Analysis*. (2011).
69. Bodin, M. Mapping university students' epistemic framing of computational physics using network analysis. *Physical Review Special Topics - Physics Education Research* **8**, 010115 (2012).

70. Carlson, C. Ray. & Wilmot, W. W. *Innovation : the five disciplines for creating what customers want*. (Crown Business, 2006).
71. Pokorny, J. J. *et al.* Network analysis for the visualization and analysis of qualitative data. *Psychological Methods* **23**, 169–183 (2018).
72. Albert, R. & Barabási, A.-L. Statistical mechanics of complex networks. *Reviews of Modern Physics* **74**, (2002).
73. Newman, M. E. J. The Structure and Function of Complex Networks. *Society for Industrial and Applied Mathematics* **45**, 167–256 (2003).
74. Paranyushkin, D. Visualization of Text's Polysingularity Using Network Analysis Dmitry Paranyushkin Visualization of Text's Polysingularity Using Network Analysis. *Nodus Lab* (2012).

CHAPTER 1. SUPPLEMENTARY MATERIAL

Introduction

The interest around climate services, their operational value and use has been increasing since their first appearance in early 2000s (Bruno Soares and Buontempo, 2019). The concept itself expanded and embraced perspectives derived from climatology and physical sciences, as well as economics and social disciplines. This allowed the investigation of technical aspects required to build science-based services (Dekker *et al.*, 2018; Troccoli *et al.*, 2018; De Felice *et al.*, 2019), as well as research on users' needs (Buontempo *et al.*, 2017; Christel *et al.*, 2018) and market and non-market dynamics that should be in place to boost their uptake (Bremer and Meisch, 2017; Webber and Donner, 2017; Damm *et al.*, 2019). Despite these efforts, a 'usability gap' (Dinku *et al.*, 2014; Kirchhoff, Lemos and Kalafatis, 2015) between providers of climate information and their potential users is still in place. Reasons for this are imputed to the existence and co-occurrence of multiple factors: inefficient underutilization of climate models as tools to support robust decision-making in a complex reality (Weaver *et al.*, 2013), poor inclusion of insights from social sciences to fully understand users' needs (Vaughan *et al.*, 2016), a good-dominant logic that fails at including users' experiences and perspectives in the co-production and co-generation process (Alexander and Dessai, 2019), as well as timeliness in meeting expectations (Ford, Knight and Pearce, 2013; Webber, 2017) among others. The implicit assumption behind this literature is the complete knowledge of what climate services are. However, there is no agreement on their definition (Vaughan and Hewitt, 2018; Bruno Soares and Buontempo, 2019) and this poses challenges in identifying what they are. In this paper, we consider "climate services" those innovations translating climate science into a user-tailored, decision-relevant tool. Examples of operational climate services are provided in Table 1.0S.

Table 1.0s | Examples of climate services

Climate service	Description	URL
IRRICLIME	Spatially-explicit, open-source tool providing short- and medium-term water budget forecasts to the target user.	https://gecosistema.com/climate-services-and-tools/
CLIME	Offers a multi-model approach to integrate high-resolution post-processed climate data, uncertainty evaluations from national to local level with the purpose of supporting decision-making.	https://www.dataclime.com/en/dataclime-en/
MAREX SPECTRON	Offering to commodity traders the "Global Seasonal Weather Outlook" to help managing risks related to soft commodities	https://climate.copernicus.eu/marex-spectron
Africa Hydromet program	A partnership of development organisations working to improve weather, water and climate services to boost local economies in Africa.	http://www.worldbank.org/en/programs/africa_hydromet_program
AgroClimas	Historical analysis, monitoring services and climate forecasts developed to support local farmers in Colombia under threat of food insecurity	https://ccafs.cgiar.org/es/agroclimas#.XQIXCYgzZPY

Materials and methods

1.1.Framework

Data. Scopus web-portal (www.scopus.com) is the largest abstract and citation database of peer-reviewed literature, with almost 70 million items and 1.4 billion cited references dating back to 1970. I run a specific query[15] in the database specifying to look for any type of document. I found 358 records at January 23rd 2019 (Table 1S). I cross-checked the initial results launching the same query to Web of Knowledge (www.webofknowledge.com) under "Topic". In this case, the sample included records from 1985 to present. Hence, the time series differed. Scopus reported a significantly larger collection (358 vs 243 records). I exported the dataset in *.bib* format to perform data cleaning on multiple software (Mendeley and TeXMaker).

Table 1.1S | Main information

Variable	
Documents	358
Sources	173
Keywords Plus (ID)	1788
Author's Keywords (DE)	770
Period	1974-2018
Average citations per documents	14.32
Authors	1427
Author appearances	1729
Author of single-authored documents	56
Authors of multi-authored documents	1371
Single-authored documents	82
Documents per author	0.251
Authors per document	3.99
Co-authors per document	4.83
Collaboration Index	4.97

I included only peer-reviewed publications in English language. Many projects have produced or are still producing material often included under "grey literature" label. This corpus comprises project deliverables, milestones, press releases, communication records, workshop and meeting reports. Given the novelty of the field, their exclusion from the sample may drive the results towards well-established and purely research-oriented actors. Furthermore, private firms and institutions are rarely involved in the peer-review process and do not take credit for publications or dissemination of their

[15] "climate service*" AND NOT "service* climate". We also run an alternative query ("climate services" AND "Climate Services" AND "climate service" AND "Climate Service" AND NOT "service* climate") to check on the validity of our first search. The two gave the exact same results.

innovation actions. Despite this limitation, the analysis is restricted to scientifically recognized works for two main reasons: *(i)* projects funded under public schemes (i.e. Horizon2020, FP7, FP6, multilateral funds and bilateral agreements) are normally developed by a consortium of partners, where research institutions may cover a portion of the workflow. However, they are normally assessed against a set of criteria that necessarily involve a peer-review process. Therefore, outcomes of projects can be reflected in scientific works and co-authorship networks capture variety of authors involved. *(ii)* Ideas, methodologies and concepts published through a peer-review mechanism are useful tools to backup the strengths behind some of the most promising and cutting-edge innovations. Hence, they serve as proxies of the most prominent topics and areas of work. The distribution of publications considered in the sample is presented at continuation (Table 1.2S).

Table 1.2S | Distribution of records per source type

Source Type	
Article	221
Article in press	6
Book	8
Book chapter	26
Conference paper	55
Editorial	3
Erratum	1
Letter	1
Note	14
Review	21
Short survey	1

Climate services have been formally defined only in 2001. Therefore, the steady growth of research (Figure 1.1S) around this topic is justified by the lack of a shared vision and a still not existent action plan. Despite the novelty of the concept, I believe the query launched on Scopus is fully valid. One could argue that every document published before 2001 should not be included in the sample of interest. However, I claim that the broad scope of “climate services” definition allows for their inclusion because it does not constitute a limitation under any circumstance. The growth rate of the overall period is 16.81%.

Bibliometrics. Bibliometrics, Scientometrics and Infometrics share the same theory and methods, but differ for fields of application and usage (Figure 1.2S). Bibliometrics has been widely employed in Engineering and Science (Tian, Wen and Hong, 2008; Larivière *et al.*, 2013), Social Sciences

(Archambault and Gagné, 2004) and others (Thomson Reuters, 2008; Zare-Farashbandi, Geraei and Siamaki, 2014). I used the *“bibliometrix”* package of R software (Aria and Cuccurullo, 2017). Despite the existence of several tools for bibliometric and science mapping tools, the use of *bibliometrix* R-package is justified by two reasons: *(i)* it works in R, an open-source environment, fully accessible to the research community; *(ii)* it allows to download data and its associated metadata from two bibliographic sources (Scopus and Clarivate Analytics WoS) and to convert them into a data frame to facilitate data mining.

Bibliometrics can provide quantitative estimates of the scientific production in a given field, but presents some frawbacks: it is not able to provide insights about the properties that interactions and collaboration patterns show, failing in considering the individual agent as part of the complex systems where microscopic dynamics affect the emergence of meso and macroscale phenomena. Bibliometrics also struggles with three additional challenges: *(i)* outcomes are often extrapolated out of context and may not reflect the quality of an individual; *(ii)* performance of authors are often not fully comparable; *(iii)* the sample size affects the reliability of the results (Belter, 2015; Ball, 2017; Suebsombut *et al.*, 2017; Martín-Martín, Orduna-Malea and Delgado López-Cózar, 2018). Therefore, it provides a partial vision of the actual success of a scholar, institution or country and requires additional and complementary tools.

First, I computed descriptive statistics for the co-authorship networks of individuals, affiliations of the main author and country of the institution they work for. Co-citation networks were explored only in a dynamic framework: I addressed the most 20 cited manuscripts throughout our sample to derive implications around the conceptual evolution of the field. For visualization purposes, I used a combination of *ggplot2* and *igraph* packages’ libraries.

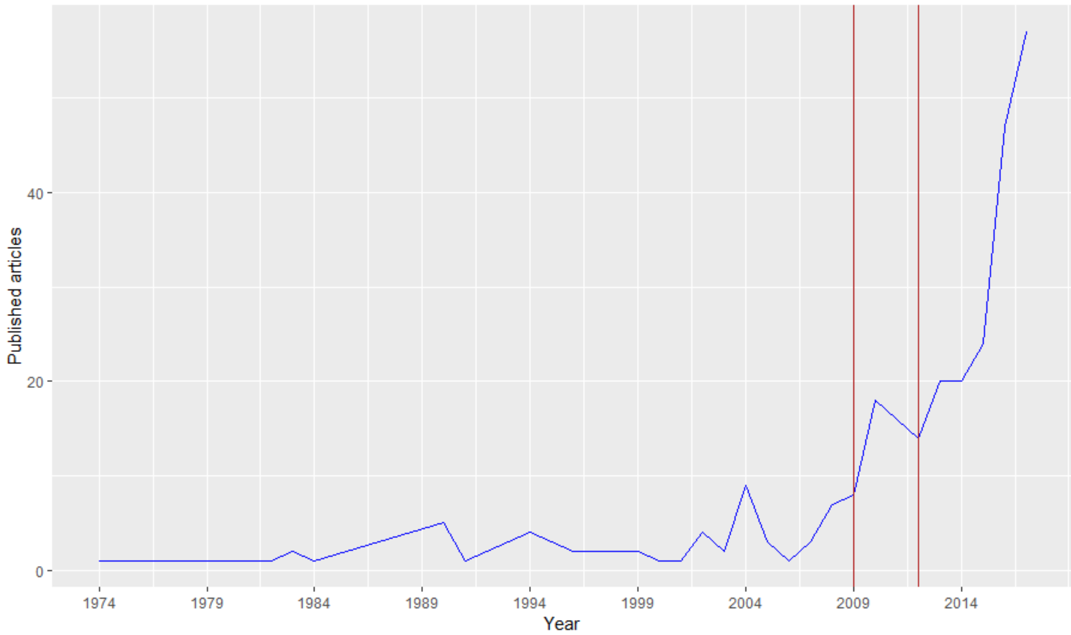


Figure 1.1S | Scientific production

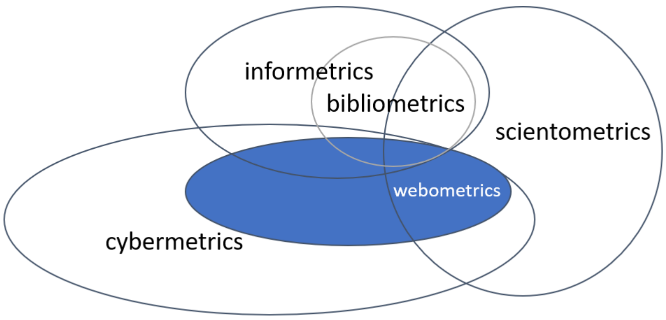


Fig 1.2S | Information science: scientific domains

The validity of the Lotka's Law of Scientific Productivity was also checked in the case of Climate Services to see whether regularities can be found. Given a set of publications (x), the relative frequency of researchers with n publications (y) and k as a field-specific constant, the Lotka's Law takes the following form:

$$x^n y = k$$

The Law states that the number of authors contributing x to the overall sample in a given timeframe is a fraction of those making a single contribution, following an inverse-quadratic form of the type $\frac{1}{x^\alpha}$, with $\alpha \approx 2$. The higher the number of articles in a given field, the less frequent the number of authors publishing that amount of publications. Given the heterogeneity of disciplines, the actual ratios – expressed as a function of α – changes. I first checked whether the Lotka's Law can be used to predict publication productivity in the field of Climate Services, examining the goodness-of-fit of the empirical distribution of our publication sample and a theoretical one using the Lotka's formula (1926). I limited the analysis to the number of publications. I obtained the goodness-of-fit from a Kolmogorov-Smirnov (K-S) two sample test, which is used to compare the functions of the two distributions and check if structural differences between the two exist. The estimation of the constant is equal to 0.58. This figure indicates that the proportion of authors publishing a single item in the field of Climate Services is almost 58%, which is slightly higher than the one predicted by Lotka. However, results from the K-S test give a goodness-of-fit of 0.95 and a p-value of 0.164, which means that no significant differences exist between the two distributions and that Lotka's Law can be adopted to predict the evolution of research on Climate Services (Figure 3S).

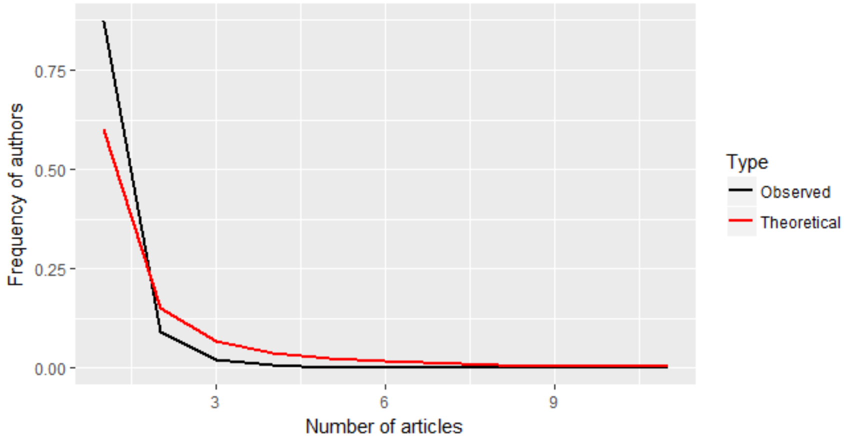


Figure 1.3S | Scientific productivity (Lotka's Law)

I ranked the top scholars, institutions and countries based on the quantity of publications produced and published (Figure 1.4S). Despite the significant presence of European entities, the United States are still largely dominating the field. Overall, national weather offices, well-established research institutions and international organisations are shaping research with their contributions. Multi-country collaborations are enhancing the existing stock of knowledge by allowing inputs to travel beyond borders.

As stated in the article, the sample under study is not taking into account any contribution belonging to the so-called "grey literature". This may possibly lead to a biased result in favor of universities and Research Performing Organisations (RPOs), which are – by mandate – required to produce scientific contributions. However, the advancements in the field of climate services are representative of the efforts made at global level: public-private partnerships are often the most appropriate frameworks where research and innovation are pursued. This holds for European-funded schemes, where representatives of both domains are asked to merge their competences and skills in order to win projects and initiatives. Nevertheless, the bibliometric results hereby presented are important to stimulate reflections about the uneven coverage of research on climate services, which appears skewed in favour of English-speaking countries and established institutions.

I run a specific analysis on the author-scientific production to explore productivity patterns (Table 1.5S), while also measuring the research impact (*quality*) through bibliometric indicators (Table

1.3S). Authors are ranked on the Dominance Factor (DF), which is a ratio indicating the fraction of papers of a given author in which she appears as first author over the total amount of papers of that author (Kumar Surendra Kumar and Kretschmer, 2008). Within the top 20 authors, 35 percent are US-based, 30 percent are working in UK institutions and 20 percent is currently in Spain. The remaining 15 percent is allocated in Indonesia, The Netherlands and South Africa. Despite the role of productivity in assigning a relative importance to authors, the research impact is signaling how appreciated are the produced works. Based on the *h-index*, Lowe R. is ranked first, followed by Hewitt C. and Buontempo C.. Given the *h-index* does not average the number of citations received, I ranked authors on their *g-index*: the top three authors are Hewitt C. (11), Buontempo C. (7) and Lowe R. (6), Vaughan C. (6) and Thomson MC. (6). The *m-index* provides the research impact of any individual scholar over their professional career in a given field of interest: Golding N. (1), Lowe R. (0.83) and Bruno-Soares M. (0.75) are the first three authors listed. Results from the bibliometric analysis also provide insights on the main subjects tackled by the top 20 scholars: Earth and Planetary Sciences (20), Environmental Sciences (20) and Social Sciences (17) are the dominant research areas. This distribution reflects the global one of the overall sample of publications considered.

Table 1.3S | Authors' ranking by productivity patterns and research impact

Author	DF	h-index	g-index	m-index
CARR ER	1	2	3	0.5
WINARTO YT	0.8	2	2	0.4
BRUNOSOARES M	0.75	3	4	0.75
VINCENT K	0.75	2	4	0.5
VAUGHAN C	0.66	3	6	0.5
ASRAR GR	0.66	3	3	0.37
BETT PE	0.66	2	2	0.66
BRÖNNIMANN S	0.66	1	2	0.5
GUIDO Z	0.6	3	5	0.42
LOWE R	0.57	5	6	0.83
DUNSTONE N	0.5	3	4	0.75
GOLDING N	0.4	3	4	1
THOMSON MC	0.33	3	6	0.33
BALLESTER J	0.33	3	3	0.6
DOBLAS-REYES FJ	0.25	4	4	0.57
RAY AJ	0.25	3	4	0.75
TALL A	0.25	2	4	0.22
TROCCOLI A	0.25	0	0	0
BUONTEMPO C	0.23	4	7	0.66
HEWITT C	0.18	4	11	0.5

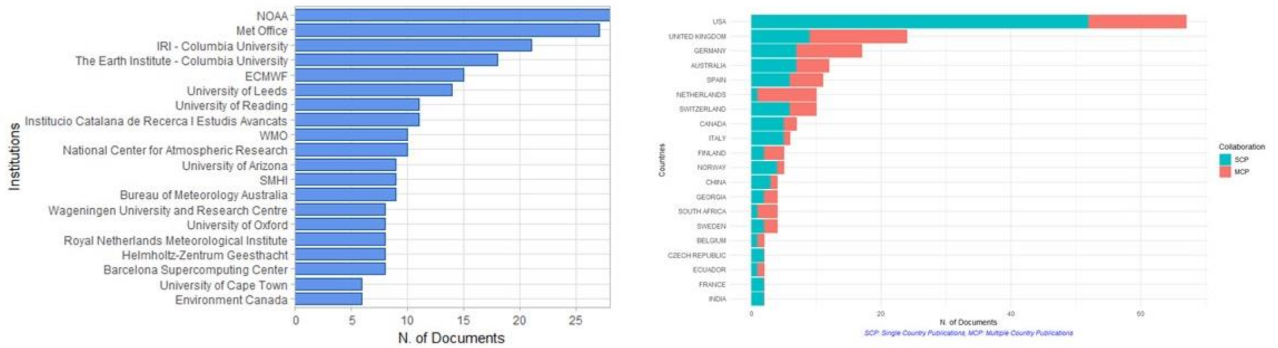


Figure 1.4S | Bibliometric results. The left-hand side reports the top institutions in the sample; the right-hand side shows the most productive countries differentiating between multi-country and single-country publication records.

Conceptual structure. The conceptual structure of our global map of climate services includes the assessment of exploration of the most relevant topics covered by the sample of authors and institutions and their temporal dynamics. I extracted the abstracts of each publication record, and I computed the most frequent terms overtime. I applied two main restrictions: (i) I accepted only terms mentioned at least 5 times (quantity); (ii) I computed a "relevance score" of the so-obtained collection, including only those with score greater than 60 percent. The relevance score is automatically obtained from the software VOSViewer: the score is lower in case the co-occurrence of terms with other phrases follows a random pattern. The score increases in case the co-occurrence of certain words occurs primarily in a limited set of sentences.

The top 10 words of our sample present all a significantly steep curve, especially in recent times (Figure 1.5S). Interest has shifted from a global to a more regional and localized perspective, hence leading to a significant turn towards adaptation. This is also confirmed by the dynamic snapshot of the network of concepts (Figure 1.6S). Research has progressively moved away from a mitigation-centered and carbon-related focus in favor of a user-centric view where decision-making becomes central. The observation of links between different concepts reinforces once more this transformation: "emission" and "mitigation" were strictly connected to "agriculture" and "land" between 2010 and 2012. Since 2014-2016, our results show an intensified connection between "farmer", "risk management" and "adaptation".

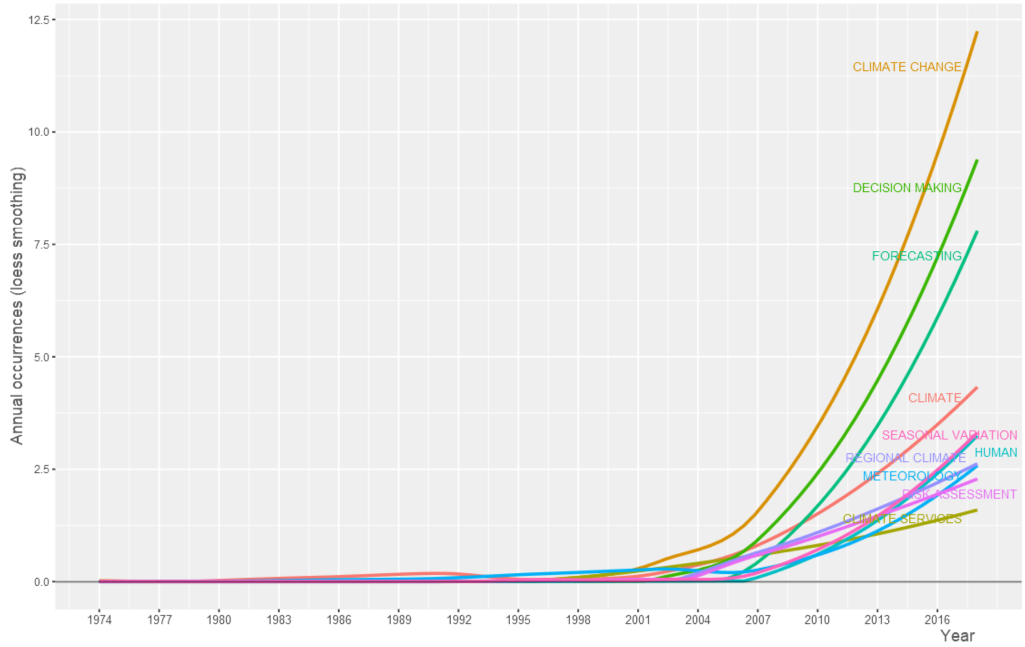


Figure 1.5S | Word growth graph: evolution of top mentioned keywords in abstracts

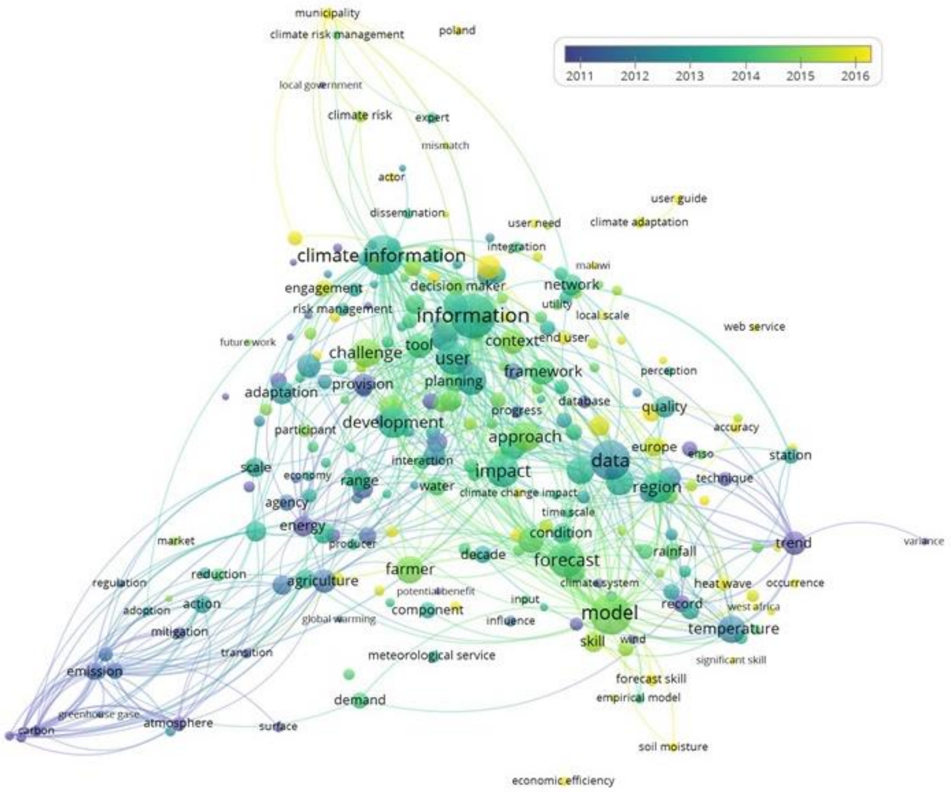


Figure 1.6S | Network of abstract keywords co-occurrence

Network Analysis. I used Social Network Analysis to uncover four main aspects: similarities, relations, interactions and patterns. The fundamental axiom behind the choice of this methodology is that "structure matters" (Otte and Rousseau, 2002; Borgatti *et al.*, 2009). I performed the analysis using a combination of *igraph*, *statnet, itergraph* and *sna* R packages on undirected graphs. For visualization purposes, I also used Gephi (https://gephi.org/) and VOSViewer (http://www.vosviewer.com/). I extracted the Giant Component of each sub-graph and I assigned the following names: $N_{ind}, N_{countr}, N_{inst}$ for individuals, countries and institutions respectively. Then, I computed the following:

1. Graph density
2. Degree distribution and average degree
3. Average path length and diameter
4. Clustering coefficient

Density is an indicator of cohesion within a graph. It gives the number of ties in a network, as a proportion of the total possible ties (which describe the case of complete graphs, where density =1). Density of N_{ind} is 0.026, which indicates a loosely connected graph. Degree distribution (Figure 1.7S) is the simple count of the number of nodes presenting each possible degree realization. High-degree nodes are typically influential within a network and have potentially more power in influencing the information flows.

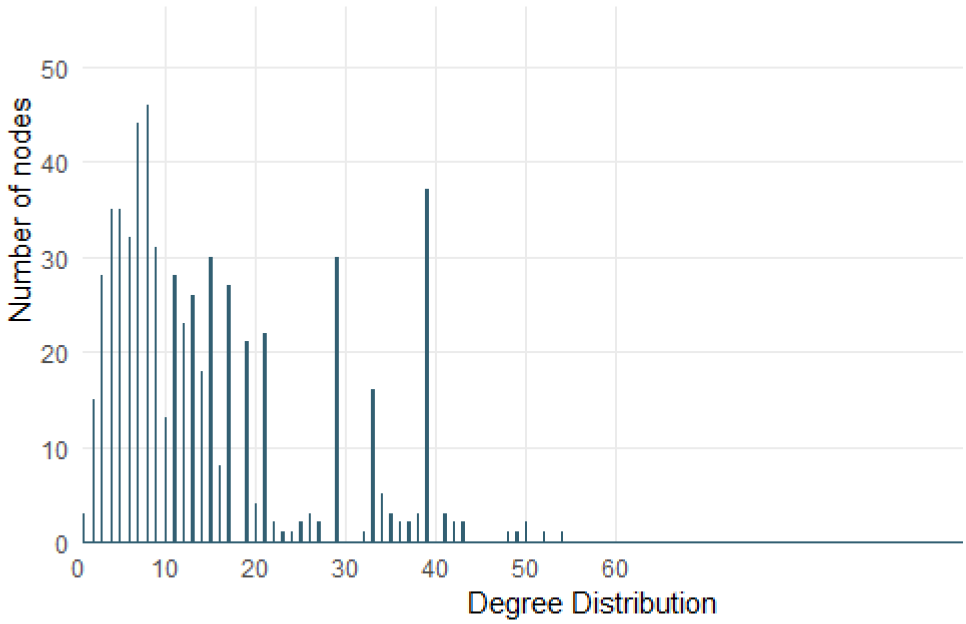


Fig 1.7S | Degree Distribution

The average degree is 15.093 and represents the average number of links touching upon a node. The average path length of the giant component of out network of individual scholars is mathematically expressed as:

$$\langle L \rangle = \frac{1}{n(n-1)} \sum_{i \neq j} d_G(v_i, v_j)$$

where $d_G(v_i, v_j)$ is the distance between two vertices, meant as the amount of edges in the shortest path running between v_i and v_j.

Equally connected to the edge dimension, the clustering coefficient estimates the probability of two neighbours of a given node to be connected to each other. The average clustering coefficient is given by

$$\bar{C} = \frac{1}{n}\sum_{i=1}^{n} C_i$$

where $C_i = \frac{number\ of\ edges \in N_i}{\frac{k_i(k_i-1)}{2}}$ is a vertex-specific (local) clustering coefficient. Local clustering coefficients represent the number of cliques to which a given node belong over the maximum number of triangles the same node could be part of.

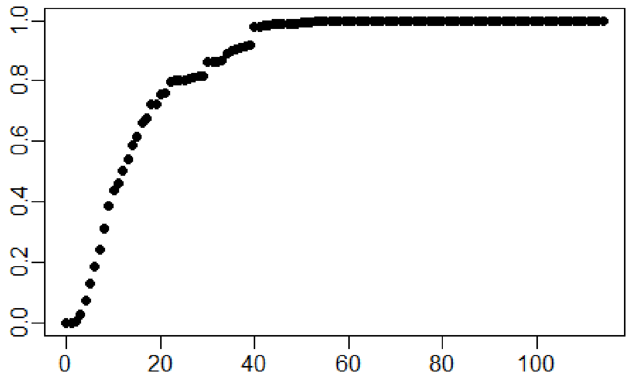


Figure 1.8S | Cumulative degree distribution function

Centrality measures. Literature on complex networks has proved them to share three main features: the "small world" property, the "scale free" effects and the "clustering" trait. A network typically displays short distances between the nodes ("small world"), which scales following a logarithmic scale with the total number of nodes (Latora and Marchiori, 2001). The second effect prescribes the existence of "hubs": few nodes with high degree and many nodes with low degree, following a power-law distribution (Boccaletti *et al.*, 2006). Finally, clustering property forecasts that each pair of nodes will be linked to a third one, forming at least a triangular shape (Estrada and Rodríguez-Velázquez, 2005). Other subgraph functional forms ("network motifs") are actually proved to be significant and they indicate patterns occurring in a graph far more frequently than in a random network with the same degree sequence (Milo *et al.*, 2002).

Centrality measures are useful numerical characterization of networks. The most common is *Degree centrality*, which quantitatively assesses the scale-free feature and broadly represents the number of links each node has with other nodes. *Degree centrality* is a measure of "popularity" of a given actor. It is expressed as the sum of all the actors directly connected to the node of interest:

$$d(i) = \sum_{j} m_{ij}$$

where $m_{ij} = 1$ if there is a link between two authors and $m_{ij} = 0$ otherwise.

In the context of social networks, *Betweenness Centrality* is also very common. It measures the number of times an individual connects a pair of other actors:

$$b(i) = \sum_{j,k} \frac{g_{jik}}{g_{jk}}$$

where g_{jk} is the number of shortest paths from j to k passing through i $(with\ j, k \neq i)$. Betweenness allows the information to circulate smoothly within their neighborhoods and, ultimately, the overall network. Therefore, authors with larger values of betweenness centrality are facilitators of knowledge flows. Whenever in presence of connected networks, it is possible to measure *Closeness centrality*, which is equal to the total distance of a given node from all the others:

$$c(i) = \frac{1}{\sum_i d_{ij}}$$

where d_{ij} represents the number of ties in the shortest path from i to j. Comparison between nodes of different sizes is possible via normalization (the average length of the shortest possible path).

The three measures emphasize different aspects, but they all depend on the graph size. Freeman (1979) pioneered in the analysis of "the effects of network size" and solved the issue introducing the point-centrality, an absolute measure allowing for interpretation of the values with respect to a [0,1] scale. In contrast with point-centrality, node-centrality is any $nc(v_i)$ function, which assigns a real value to every node of an undirected and connected graph $G = (V, E)$ with $|V| = n$. Hence, $nc(v_i)$ is a node-centrality of a node v_i if

$$(i)\ \ nc(v_i) \in [0,1] \qquad for\ every\ v_i \in V, \text{ and}$$

$$(ii)\ \ nc(v_i) = 1 \qquad iff\ G = S_{1,\ n-1}\ amd\ i = 1$$

Eigenvector centrality is also related to connected components of the graph. It provides the most appropriate simulation of a case where each node has simultaneous effect on its neighborhood. It is mathematically expressed as "the principal or dominant eigenvector of the adjacency matrix A" (Estrada and Rodríguez-Velázquez, 2005) representing the considered connected subgraph:

$$x_v = \frac{1}{\lambda} \sum_{t \in M(v)} x_t = \frac{1}{\lambda} \sum_{t \in G} a_{v,t} x_t$$

where $G \coloneqq (V, E)$ is a given graph defined over a set of vertices and edges; $A = \left(a_{v,t}\right)$ is the adjacency matrix; $M(v)$ is the set of all the neighbors of v and λ is a constant. Note that $a_{v,t} = 1$ if vertex v is linked to vertex t, and $a_{v,t} = 0$ otherwise. Eigenvector centrality can be interpreted as an extension of degree centrality. Throughout the past 50 years, multiple centrality measures have been computed and used for a variety of complex networks. Table 4S provides a list of the most commonly observed, with their relative mathematical formulation and their interpretation.

Table 1.4S | Centrality measures used in this work

Measure	Definition	Mathematical formulation	Explanation	Source
Average distance	Average distance of node u to the rest of the nodes in the network	$\boldsymbol{C_{AV}(u) = \frac{\sum_{w \in V} d(u,w)}{n-1}}$	The measure requires strongly connected networks. It is the inverse of closeness centrality.	(Del Rio, Koschützki and Coello, 2009)
Barycenter centrality	The inverse of total distance between a given node and all the others. Running these scores require to rank one subgraph at a time.	$\frac{\boldsymbol{1}}{\boldsymbol{d(v, all\ other\ vertices)}}$	Closeness scores are calculated on the average distance between a vertex and all the others. Barycenter scores use the total. More central nodes in a connected subgraph will present overall shortest paths.	(Ashtiani *et al.*, 2017)
Betweenness centrality	The number of times an individual connects a pair of nodes.	$\boldsymbol{b(i) = \sum_{j,k} \frac{g_{jik}}{g_{jk}}}$ where $\boldsymbol{g_{jk}}$ is the number of shortest paths from j to $\boldsymbol{k}$ passing through $\boldsymbol{i}$ $(\boldsymbol{with\ j, k \neq i})$.	In co-authorship networks, the measure gauges the extent to which a node facilitates the flow of information in the network. Therefore, it is a measure of potential control in a graph.	(Otte and Rousseau, 2002; Estrada and Rodríguez-Velázquez, 2005)
BottleNeck centrality	A tree $\boldsymbol{T_v}$ of shortest paths is drawn from node v; $\boldsymbol{n_v}$ is the number of shortest paths included in $\boldsymbol{T_v}$. Extract all nodes s in $\boldsymbol{T_v}$,	$\boldsymbol{BV_v = \sum_{s \in V} P_s(v)}$ with $\boldsymbol{T_s}$ be the tree of shortest paths rooted at node s; $\boldsymbol{P_s(v) = 1}$ if more	The high-betweenness characteristic of nodes that tend to share similar functions and find themselves as	(Yu *et al.*, 2007)

	such that more than $\frac{nv}{4}$ meet at node s. Nodes extracted in this way are “bottlenecks” of T_v.	than $\frac{\lvert V(T_s)\rvert}{4}$ paths from node s to other nodes in T_s meet at v and $P_s(v) = 0$ otherwise.	“between” highly interconnected subgraph clusters. Removing these edges could partition the network.	
Closeness centrality (Freeman)	An inverse measure of centrality, equal to the total distance of a given node from all the others). It is computed as the inverse of the sum of distances to all other nodes	$$c(i) = \frac{1}{\sum_i d_{ij}}$$ where d_{ij} represents the number of ties in the shortest path from i to j.	How far each actor is located from all the others. It often interpreted as either an indication of efficiency or of independence. It is related to betweenness because they are both expressed as function of the shortest path and they conceptually share a duality in terms of dependency:	(Ruhnau, 2000; Otte and Rousseau, 2002; Brandes, Borgatti and Freeman, 2016)
Closeness centrality (Latora)	Expressed as the sum of the inversed distances to all other nodes.	$$\sum_{i \neq j} \frac{1}{d_{ij}}$$ where d_{ij} represents the number of ties in the shortest path from i to j.	Variant of the Freeman algorithm, suitable for networks with disconnected components.	(Latora and Marchiori, 2001; Crucitti, Latora and Porta, 2006; Opsahl, Agneessen s and Skvoretz, 2010)
Closeness vitality	The change in the sum of distances between all node pairs when excluding a given node. It	$$C_{CV}(x) = I_W(G) - I_W\left(\frac{G}{\{x\}}\right)$$ where $I_W(G)$ is the Wiener Index:	It requires a strongly connected network and denotes how much will the relationship	(Brandes, Erlebach and Gesellscha ft für Informatik., 2005)

	requires the computation of the Wiener Index	$$I_W(G) = \sum_{v \in V} \sum_{w \in V} d(v, w)$$	change in an all-to-all communication if a given element x is removed form the graph	
ClusterRank	A measure inspired by PageRank and LeaderRank capable of accounting for the number of neighbors, neighbors' influences and clustering coefficient of a given node.	$$s_i = f(c_i) \sum_{j \in \Gamma_i} (k_j^{out} + 1)$$ where $f(c_i)$ includes the effects of the local cluster of *i*, while the +1 term results from the contribution of the j node itself. The clustering coefficient of a directed network is: $$c_i = \frac{\left\lvert \{e_{jk} \mid j, k \in \Gamma_i\} \right\rvert}{k_i^{out}(k_i^{out} - 1)}$$ with k_j^{out} is the out-degree of *i*, which represents the number of followers of node *i* and Γ_i if the set of followers of I, $\{e_{jk} \mid j, k \in \Gamma_i\}$ is the set of links connecting two of *i*'s followers.	Typically applied to directed networks, it can be used in undirected graphs where ClusterRank is significantly higher than degree centrality and k-core decomposition.	(Chen *et al.*, 2013; Wang *et al.*, 2017)
Clustering coefficient	Local clustering coefficient of a node n_i is a measure of the cliquishness of n_i neighborhood. Global clustering coefficient is the average of local clustering coefficients.	$$c_i = \frac{y_i}{\binom{d_i}{2}}$$ where y_i is the number of links between the neighbors of n_i and d_i is its degree. $$C = \frac{1}{N} \sum_{i \in N} c_i$$	The local clustering coefficient can be viewed as a local density measure in the neighborhood of a node i. In the case of undirected graphs, the global clustering coefficient is the number of closed triplets over the total number of closed triplets.	(Hernández and Mieghem, 2011; Fouss, Saerens and Shimbo, 2016)

Current-Flow Closeness Centrality	Alternative measure of distance between two nodes, treated as differentiated electric potential in the case of an electric network.	$C_u = \frac{n}{\sum_{v \in V}(v_{uv}(u) - v_{uv}(v))}$ with $u \neq v$; $v_{uv}(u)$ is the absolute potential of vertex u, based on the power supply from vertex u to vertex v; $(v_{uv}(u) - v_{uv}(v))$ is an alternative measure of distance or, in the case of an electric network, the effective resistance measured in voltage.	Appropriate t measure critical nodes in the network. Current-Flow closeness measures how easily others can access a node and viceversa. Limit: the measure cannot assess which nodes impact more on the total network current-flow efficiency once a node fails.	(Li *et al.*, 2018; Liu and Yan, 2018)
Communicability Betweenness centrality	Let $G = (V, E)$ be an undirected graph and be A the adjacency matrix of G. Let $G(r) = (V, E(r))$ be the graph obtained by removing all edges connected to node r, but not r itself. The adjacency matrix becomes A+E(r), where E(r) has nonzero values in row and column r.	$\omega_r = \frac{1}{C}\sum_p \sum_q \frac{G_{prq}}{G_{pq}}$, $p \neq q, p \neq r, q \neq r$ whit $G_{prq} = (e^A)_{pq} - (e^{A+E(r)})_{pq}$ is the number of random walks involving vertex r; $G_{pq} = (e^A)_{pq}$ is the number of closed walks starting at p and ending at q; $C = (n-1)^2 - (n-1)$ is a normalization factor. The measure takes values [0,1].	Derived from the concept of shortest path, it takes into account the shortest path between nodes and all the paths between nodes.	(L.D and Raj, 2017)
Community centrality	The sum of local influence zones of all network edges and nodes, including the one under study.	$C_C(i) = \sum_{i \in j}^{N} (1 - \frac{1}{m} \sum_{i \in j \cap k}^{m} S(j,k))$ where the main sum is expressed over the total N communities to which	A community is ultimately a subgraph depicting a set of interacting agents. The measure uses the pairwise similarity	(Kalinka and Tomancak, 2011; Konstantinidis, Papadopoulos and Kompatsiar

		node i belongs to; m is the number of communities paired with community j and to which node i jointly belongs; $\boldsymbol{S(j,k)}$ is computed using the Jaccard coefficient for the number of shared nodes between community j and k.	between detected communities as weights for the number of communities a given node belongs to.	is, 2017)
Dangalchev Closeness Centrality	It is a variation of closeness centrality.	$$\boldsymbol{C(i) = \sum_{j \neq i} \frac{1}{2^{d(i,j)}}}$$ where d(i,j) is the distance between two nodes.	It is aimed at assessing the network's resistance after the removal of individual links or nodes.	(Dangalchev, 2006a)
Decay centrality	Based on proximity between a given node and every other weighted by a decay.	$$\boldsymbol{\sum_{y \in V(G)} \delta^{d(x,y)}}$$ where δ is a parameter taking values [0,1]	The prerequisite is the existence of a strongly connected network.	(Tsakas, 2017)
Degree centrality	Number of ties a node has	$$\boldsymbol{d(i) = \sum_{j} m_{ij}}$$ where $\boldsymbol{m_{ij} = 1}$ if there is a link between two authors and $\boldsymbol{m_{ij} = 0}$ otherwise.	In co-authorship networks, degree expresses the number of authors in the graph with whom she has co-authored at least one article.	(Otte and Rousseau, 2002)
Diffusion Degree	The cumulative distribution score of the node itself and its neighbors	$$\boldsymbol{C_{DD}(v) = C'_{DD}(v) + C''_{DD}(v) = \lambda_V * C_D(v) + \sum_{i \in neighbors(v)} C'_{DD}(v) = \lambda_V * C_D(v) + \sum_{i \in neighbors(v)} \lambda_i * C_D(i)}$$ where $\boldsymbol{C'_D(v)}$ represents the contribution of node v in the diffusion process;	Differently from other measures, Diffusion degree considers neighbors' contributions in addition to the degree of a given node. Furthermore, DD works accurately with	(Pal, Kundu and Murthy, 2014)

		$C''_{DD}(v)$ is the total contribution of neighbors of v; λ is the propagation probability of a given node to activate another node	not uniform propagation probability distributions.	
DMNC – Density of Maximum Neighborhood Component	Ratio between the number of edges of the Maximum Neighborhood Component of a given node v and the number of nodes elevated to a given parameter, conveniently set to describe the number of communities in the neighborhood sub-network of v.	$\frac{\lvert E(MNC(v))\rvert}{\lvert V(MNC(v))\rvert^{\varepsilon}}, 1 \leq \varepsilon \leq 2$	Neighborhood-based measure, capable of undercovering unrecognized hubs within a given network	(Chin and Samanta, 2003; Lin *et al.*, 2008)
Eccentricity centrality	The greatest distance between vertex v and any other vertex in the network.	$C_E(v) = \frac{1}{\max\{dist(u,v): u \in V\}}$	An eccentricity with high values implies a greater node proximity. If eccentricity is low, there is at least one node far from node v.	(Hage and Harary, 1995; Hernández and Mieghem, 2011; Takes and Kosters, 2013)
Eigenvector centrality	The principal or dominant eigenvector of the adjacency matrix A of the connected subgraph	$x_v = \frac{1}{\lambda}\sum_{t\in M(v)} x_t = \frac{1}{\lambda}\sum_{t\in G} a_{v,t}x_t$ where $= (a_{v,t})$ is the adjacency matrix; $M(v)$ is the set of all the neighbors of v and λ is a constant. Note that $a_{v,t} = 1$ if vertex v is linked to vertex t, and $a_{v,t} = 0$ otherwise	Eigenvector centrality can be interpreted as an extension of degree centrality.	(Ruhnau, 2000; Estrada and Rodríguez-Velázquez, 2005; Fletcher and Wennekers, 2018)

Entropy centrality	Centrality of nodes is measured depending on their contribution to the entropy of the graph.	$H_{ce}(G) = -\sum_{i=1}^{n} \gamma(v_i) \times \log_2 \gamma(v_i)$ where $\gamma(v) = \frac{paths(v_i)}{paths(v_1, v_2, \dots, v_M)}$ represents the total number of geodesic paths from node v to all the others over the total number of geodesic paths M existing across all nodes.	The measure provides information on the degree of centrality for a node in the graph	(Nie *et al.*, 2016)
EPC – Edge Percolated Component	Assign a removing probability p to every edge of a connectivity network G. G' is the realization of a random edge removing from G. If two nodes v and w are connected within G', then $d_{vw} = 1$ and 0 otherwise. The percolated connectivity of v and w, c_{vw}, is the average of d_{vw} over realisations. The EPC is the size pf the percolated component.	$EPC(v) = \frac{1}{\lvert v \rvert} \sum_{k=1}^{1000} \sum_{t \in V} \delta_{vt}^{k}$ where $\delta_{u,v} = \begin{cases} 0 \ if \ (u,v) \notin E' \\ 1 \ if \ (u,v) \in E' \end{cases}$ is the Kronecker delta function defined on the set of initial edges	A proportion of edges are randomly removed from the graph. The measure shows the impact of removing communication channels between individuals	(Dokas *et al.*, 2017)
Geodesic K-path centrality	The number of geodesic paths up to length k emanating from a given node	$C^K = W'$ where W is a matrix in which w_{ij} is the number of paths of length k or less from node i to j.	It is the measure of direct involvements that a given node has within the geodesic structure of the network.	(Borgatti and Everett, 2006; Agneessens, Borgatti and Everett, 2017; Dokas *et*

				al., 2017)
Harmonic centrality	It is the sum of all the inversed distances between every pair of distinct nodes.	$\sum_{i \neq j} \frac{1}{d(i,j)} = \sum_{d(i,j)<\infty, i \neq j} \frac{1}{d(i,j)}$	It is an extension of closeness centrality. Instead of using average distances, harmonic centrality employs harmonic mean of all distances. Hence, it accounts also for nodes j that cannot reach nodes i. It can be applied to not weel connected graphs, too.	(Boldi and Vigna, 2014)
Hubbell Index	Based on the Leontief's input-output model.	$C_{Hubb} = E + WC_{Hubb}$ Where E is an exogenous input and W is a weight matrix derived from the adjacency matrix A.	The measure requires connected and free loop networks.	(Hubbell, 1965)
Information centrality	The relative drop in network efficiency originated by the removal form the graph of the edges incident in node *i*.	$C_i^I = \frac{\Delta E}{E} = \frac{E[G] - E[G']}{E[G]}$ where G is a graph of N nodes and K edges and G' is the graph with N nodes and $K - k_i$ edges. Efficiency of G (E[G]) is: $E[G] = \frac{1}{N(N-1)} \sum_{i,j \in G, i \neq j} \frac{d_{ij}^{Eucl}}{d_{ij}}$	The measure relates the importance of a given node to the capacity of the network to react to the deactivation of the node. Network performance is assessed through an indicator of efficiency.	(Crucitti, Latora and Porta, 2006; Ferreira *et al.*, 2016; Das, Samanta and Pal, 2018)

K-core decomposition	A subgraph $\boldsymbol{H} = (\boldsymbol{C}, \boldsymbol{E}\vert\boldsymbol{C})$, induced by a subset of vertices $\boldsymbol{C} \subseteq \mathbf{V}$ is a k-core or a core of order k iff $\forall \boldsymbol{v} \in \boldsymbol{C}: \boldsymbol{degree_H}(\boldsymbol{v}) \geq \boldsymbol{k}$ and H is the maximum subgraph with this property	$\boldsymbol{k_i} = \sum_{j}^{N} \boldsymbol{d_{ij}}$ where $\boldsymbol{k_i}$ is the node degree of i and j is the number of nodes connected to i. Note that: $\begin{cases} \boldsymbol{d_{ij} = 1\ if\ i\ and\ j\ connec} \\ \boldsymbol{d_{ij} = 0\ otherwise} \end{cases}$	The measure allows the identification of particular subsets of the graph, named k-cores, each of which is obtained removing all the vertices of degree $\leq \boldsymbol{k}$, until the degree of those left is equal to k.	(Alvarez-Hamelin *et al.*, 2005; Al-garadi, Varathan and Ravana, 2017)
Katz Centrality	Weighted count of the number of walks starting or ending at a given node.	$\boldsymbol{x_i} = \boldsymbol{\alpha} \sum_{j} \boldsymbol{A_{ij} x_j} + \boldsymbol{\beta}$ Where A is the adjacency matrix with eigenvalues λ; β controls the initial centrality and $\boldsymbol{\alpha} < \frac{\boldsymbol{1}}{\boldsymbol{\lambda}}$	It measures the number of immediate neighbors (first degree) plus all other nodes in the network that connect to the node through the first degree ones.	(Borgatti and Everett, 2006; Fletcher and Wennekers, 2018)
Kleinberg's centrality scores	The authority score at node i, $\boldsymbol{x_i^a}$, is equal to the normalized (weighted) sum of hub scores of all nodes pointing to i. The hub score of a node i is equal to the (weighted) sum of the authority scores that hub node i links to.	$\boldsymbol{x^h} = \boldsymbol{AA^T}$ $\boldsymbol{x^a} = \boldsymbol{A^T A}$	Hubs and authorities should intuitively hold two properties: (a) a good hub is a page cited by many authorities. The larger the number of authorities and the highest their quality, the larger is the hub score; (b) a good authority is being cited by many (large hub score). Therefore, the larger the	(Kleinberg, 1998; Fouss, Saerens and Shimbo, 2016)

			number of hubs and their quality, the larger the authority score.	
Laplacian centrality	The centrality of a given vertex v is characterized as a function in terms of its Laplacian energy, a measure capturing the ability of the network to respond to the deactivation of that vertex from the graph.	$C_L(v_i, G) = \frac{(\Delta E)_i}{E_L(G)}$ where $(\Delta E)_i = E_L(G) - E_L(G_i)$ is the variation of Laplacian energy and must be nonnegative.	It requires weighted networks and allow a better evaluation of “intermediate” information around a vertex. The Laplacian centrality method values both the number of connections a vertex has and the importance of those nodes to which a given vertex is connected to.	(Qi *et al.*, 2012, 2013)
Leverage centrality	Measure to count the difference of degree between a node and its neighbors. In the average case, positive and high values implies a higher influence of a node on s neighbors.	$l_i = \frac{1}{k_i} \sum_{N_i} \frac{k_i - k_j}{k_i + k_j}$ where k_i is the degree of a given node and k_j is the degree of its neighbors. The measure is then averaged by the number N of all neighbors.	The measure allows the identification of the most relevant nodes within their own neighborhood (“critical network nodes”)	(Joyce *et al.*, 2010; Dokas *et al.*, 2017)
Lin centrality	The normalized closeness centrality measure (considered as the inverse of the average distance in the graph) multiplied by the	$\frac{\{y \mid d(y,x) < \infty\}\|^2}{\sum_{d(y,x) < \infty} d(y,x)}$ For a nonempty reachable set.	Used in the specific case of graphs with infinite distances. Nodes with larger reachable sets are more important.	(Boldi and Vigna, 2014)

	square of the number of reachable nodes.		However, given that the average distance is the same, the measure is re-multiplied by the number of reachable nodes.	
Load centrality	It weights shortest paths according to their probability of being selected in a random walk on a directed graph of shortest paths from node I to node k.		Alternative measure to betweenness and optimal for the analysis of flow structures operating below their capacities. Given an input of flow x arriving at v with destination v', v splits x in equal parts among all neighbors of minimum geodesic distance to the target.	('Package "sna": Tools for Social Network Analysis', 2016)
Lobby Index (Centrality)	The largest integer k such that a node x has at least k neighbors with a degree of at least k.	$\boldsymbol{l(x) = \max\{k: \deg(y_k) \geq k\}}$ where $\boldsymbol{\deg(y_k)}$ is the degree of x's neighbors $\boldsymbol{y_i}$ with $\boldsymbol{\deg(y_1) \geq \deg(y_2)}$ ...	The lobby index is closer to closeness centrality, betweenness and eigenvector centrality measures.	(Korn, Schubert and Telcs, 2009; Campitelli *et al.*, 2013)
MNC – Maximum Neighborhood Component	The neighborhood of a given node v, expressed as nodes adjacent to v, induces a subnetwork N(v). The MNC score of a node	$\boldsymbol{MNC(v) = \lvert V(MC(v)) \rvert}$		(Lin *et al.*, 2008; Kabir *et al.*, 2017)

	v is defined by the size of the maximum connected component of N(v)			
Markov Centrality	The average of the average Mean first-passage time (MFPT) in the Markov chain.	$$C_M(v) = \frac{n}{\sum_{s \in V} m_{sv}}$$ where $$m_{st} = \sum_{n=1}^{\infty} n f_{st}^{n}$$ is the MFPT, or the expected number of steps starting at node s taken until the first arrival at node t.	The measure requires directed and weighted networks. It uses the concept of random walks through the graph and it uses the MFPT as a measure of how tight the connection between a given node and every other vertex of the network is. Random walks reach quicker well-connected vertices. Therefore, this method helps measuring distances, that can eventually be used as ranking between nodes.	(Boldi and Vigna, 2014)
Radiality Centrality	The shortest path between node v and all other nodes in the graph. The value of each path is removed by the value of the maximum possible distance	$$C_{rad}(v) = \frac{\sum_{w \in V}(\Delta G + 1 - dist(v, w}{n-1}$$	If the shortest paths are short, the radiality centrality will be high – given that they are subtracted by the maximal possible	(Cueno and Imai, 2018; Ivanov, Gorlushkina and Ivanova, 2018)

	between nodes (diameter) +1. Resulting values are summed together and so obtained numerical value is divided by the total number of nodes -1.		distance (the diameter). Overall, if radiality has high values, with respect to the diameter, the node is closer to other nodes. If radiality is low, then the node is peripheral. Results are meaningful when compared to the average of graph.	
Residual closeness centrality	Be $\boldsymbol{d_k(i,j)}$ be the distance between i and j, originated from the original graph where all links of node k are deleted. Using the definition of closeness, we can derive a modified version.	$$\boldsymbol{C_k = \sum_i \sum_{j \neq i} \frac{1}{2^{d_k(i,j)}}}$$ The vertex residual closeness is $$\boldsymbol{R = \min_k \{C_k\}}$$ The link residual closeness is $$\boldsymbol{R = \min_{(k,p)} \{C_{(k,p)}\}}$$	More sensitive than other measures, because it is able to capture the effects of a node removal even if this does not produce any disconnected components.	(Dangalchev, 2006b; Chen *et al.*, 2013)
Semi local centrality	The measure considers the nearest and the next nearest neighbors of node, which introduces a trade-off between low-relevant degree centrality and other consuming measures.	$$\boldsymbol{Q(u) = \sum_{w \in \Gamma(u)} N(w)}$$ $$\boldsymbol{C_L(v) = \sum_{u \in \Gamma(v)} Q(u)}$$ Where Γ(u) is the set of all the nearest neighbors of node u; N(w) is the number of the nearest and the next nearest neighbors of node w.	High performing measure in low computational complexity	(Chen *et al.*, 2013)

Shortest-Paths Betweenness Centrality				
Stress centrality	Stress is computed as the measure of the shortest paths passing through a node.	$C_s(v) = \sum_{s \neq t \neq v \in V} \rho_{st}(v)$ Where $\rho_{st}(v)$ is the number of shortest paths passing through v. The same definition applies to links: $c_s(e) = \sum_{s \in V} \sum_{t \in V} \sigma_{st}(e)$ where $\sigma_{st}(e)$ denotes the number of shortest paths containing edge e.	A node is highly stressed if it is transversed by a high number of nodes. The measure itself does not automatically imply that node v is a critical one to maintain communications within the graph	(Scardoni, Petterlini and Laudanna, 2009; Zheng *et al.*, 2017)
Subgraph centrality	The sum of closed walks of different lengths in the network that starts and ends on vertex i.	$C_S(i) = \sum_{k=0}^{\infty} \frac{\mu_k(i)}{k!}$ where $\mu_k(i) = (A^k)_{ii}$ are the local spectral moments defined as the ith diagonal entry of the kth power of the adjacency matrix A.	The measure characterizes nodes according to their participation in structural subgraphs of G. Contribution of walks decreases as the length of the walk increases (due to the “small world” property).	(Estrada and Rodríguez-Velázquez, 2005)
Topological coefficient	Number of neighbors shared between a pair of nodes, n and m, plus one if there exists a direct link between the two, divided by the number of	$T_n = \frac{avg(J(n,m))}{k_n}$ Where $J(n,m)$ is defined for all the nodes sharing at least one neighbor with n.	It is a relative measure of the extent to which a node shares neighbors with other nodes.	(Deng, Zhu and Huang, 2016)

	neighbors of node n.			

Principal Component Analysis. The 42 centrality measures listed in Table 1.4S were detected automatically via the R package CINNA. Depending on the topology of the network under study, a specific function detects the optimal number of metrics to be used. I launched a PCA on the 42 measures and then I assessed their correlation and their contribution to each factor.

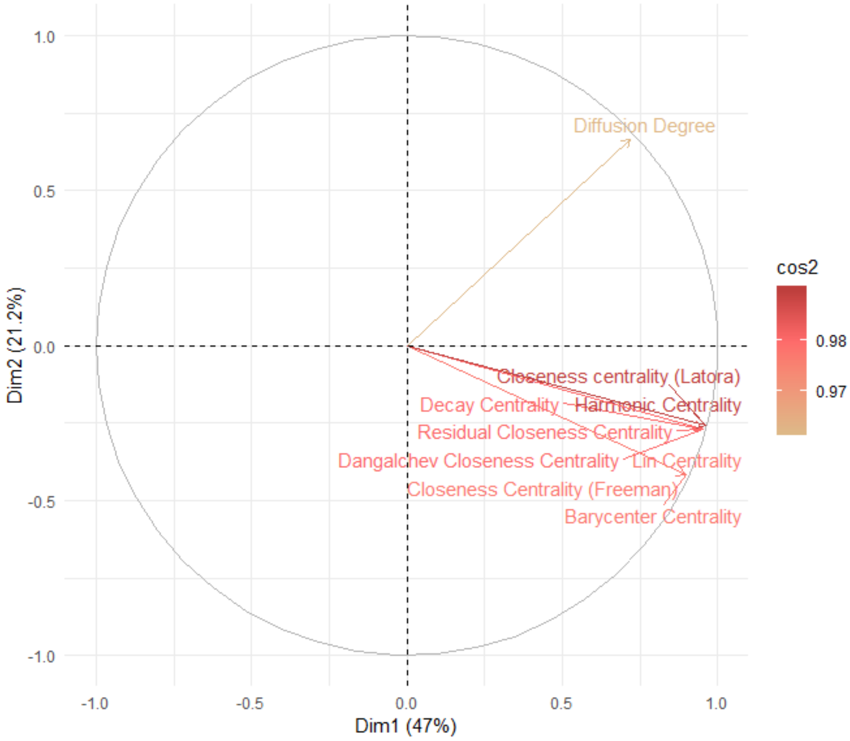


Figure 1.9S | Most correlated centrality measures as expressed by $\cos^2$

Community detection. Communities are groups of nodes strongly connected within themselves and poorly linked to each other (Barabasi, 2016). They play a significant role in understanding the spread and diffusion of epidemics (Johnson, de Roode and Fenton, 2015), economic inequality (Nishi *et al.*, 2015), diversity in social networks (Becker, Brackbill and Centola, 2017; Han *et al.*, 2017) and consensus (Baronchelli, 2018). Knowledge about the structure of the network and the groups offers the opportunity to predict where critical connectors are, hence, the chance to manipulate the graph. This "power" can be very helpful in driving and increasing the efficiency of processes. Real word networks often present structured groups: there exists a wealth of algorithms to perform community detection, but the main methods still remain hierarchical clustering. Therefore, the main question lies in the optimality of the algorithm used to perform community detection. In fact, the challenge lies in the speed of the Bell number: the number of ways allowing the partition in communities grows faster than exponentially with the size of the graph (Barabasi, 2016). Community detection is a major field of investigation in network science: Scopus reports 5320 documents, 41.6% in the Computer Sciences domain[16].

Graph clustering algorithms may be: *(i)* hierarchical methods; *(ii)* spectral methods; or *(iii)* modularity-based methods. Each solution presents advantages and bottlenecks and it may be more appropriate for certain networks, rather than generically applicable to every type. Hierarchical clustering methods comprise agglomerative or divisive procedures. The former populates an empty graph of nodes with edges, ranging from "stronger" to "weaker" connections. Conversely, the latter removes links from a complete graph in every iteration, recomputing at every step the weights assigned. I computed four community detection algorithms: the Newman-Girvan, the Greedy Community, the Spectral Community and the Louvain method. In order to assess their performance and choose between the available outcomes, I used the modularity criterion.

Modularity is a structural measure in network science. It is "the fraction of the edges that fall within the given groups minus the expected fraction if edges were distributed at random" (Li and Schuurmans, 2011). It is mathematically expressed as a difference between two ratios:

$$Q = \sum_{i=1}^{k} (e_{ii} - a_i^2)$$

where e_{ii} is the percentage of edges falling under module i and a_i^2 is the probability that a random edge falls into module i. Extending the above mathematical formula, modularity is defined as:

$$Q = \frac{1}{2m} \sum_{ij} \left(A_{ij} - \frac{k_i k_j}{2m} \right) \delta(C_i, C_j)$$

where A_{ij} is the adjacency matrix, $k_i \text{ and } k_j$ are degrees of nodes i and j, m is the number of edges, C_i is the community to which node i belongs and $\delta(.)$ is the Kronecker function that takes values 1 if $C_i = C_j$ and 0 otherwise. Modularity has useful properties that may be used to check the quality of the partitioning: *(i)* high values of modularity implies a better portioning, given $Q \in [-1,1]$; *(ii)* $Q = 0$ when the network is observed as a single community. For values $0.3 < Q < 0.7$ the community structure is significantly valid. The community structure with maximal modularity is the optimal one. I are hereby presenting the characteristics of each of them and discussing further the outcome and comparing their performance.

The Newman-Girvan algorithm. The Newman-Girvan algorithm (Newman and Girvan, 2004b) is a divisive community detection method. It builds upon edge betweenness, a value that equalizes edge weights to the number of shortest paths crossing the edge. It is an extension and generalization of

[16] The query "community detection" was launched in January 21st 2019

central vertex betweenness that provides the quantification of the influence of a given node on the others. Edge betweenness is mathematically expressed as:

$$eb(v) = \sum_{s \neq v \neq t} \frac{\sigma_{st}(v)}{\sigma_{st}}$$

Where the numerator represents the number of shortest paths from s to t including v and the denominator includes all the shortest paths from s to t. The algorithm:

(i) starts with one node

(ii) computes edge betweenness for every edge of the network

(iii) removes the edges with highest edge betweenness and

(iv) recomputes edge betweenness with the remaining ones.

Steps are iteratively repeated until every edge is removed. Given the order in which edges with highest weight is not defined, the implementation of the algorithm may produce different results. Therefore, the best partition is provided by modularity.

The Greedy community algorithm. The Greedy algorithm is the first modularity-maximisation algorithm ever conceived (Newman, 2004). It is built on the "Maximal Modularity Hypothesis", which states that "for a given network, the partition with maximum modularity corresponds to the optimal community structure" (Barabasi, 2016). The algorithm works iteratively according to the following steps:

(i) each node constitutes a community on its own for the total amount of N communities of N single nodes

(ii) compute the modularity difference ΔM for each pair of connected communities, obtained as outcome of a merging procedure. Identify the pair for which ΔM is higher and merge them

(iii) repeat the second step until all the nodes form a single community

(iv) select the partition with the maximal value of M

This is a hierarchical agglomerative method: the outcome is – as in the N-G case – a dendrogram where different cuts provide alternative partitions.

The Spectral community method. This algorithm builds on the eigenvectors of the normalized Laplacian matrix (Newman, 2013). The Laplacian is normalized by the size of identified clusters.

Modularity is expressed as:

$$Q = \frac{1}{2m}\sum_{ij}\left[A_{ij} - \frac{k_i k_j}{2m}\right]\delta_{g_i}\delta_{g_j}$$

where $\delta = 1$ if i and j are in the same community.

For simplicity, I consider only two clusters. I introduce the Ising spin variable that takes values $s_i = 1$ if i belongs to the first group and $s_i = -1$ if included in group 2. The Kronecker function can be conveniently rewritten as $\delta_{g_i}\delta_{g_j} = \frac{1}{2}(s_i s_j + 1)$. Hence, the modularity assumes the form:

$$Q = \frac{1}{4m}\sum_{ij}[A_{ij} - \frac{k_i k_j}{2m}](s_i s_j + 1)$$

I substitute $B_{ij} = A_{ij} - \frac{k_i k_j}{2m}$ to rewrite the modularity as $Q = \frac{1}{4m}\sum_{ij} B_{ij}(s_i s_j + 1) = \frac{1}{4m}\sum_{ij} B_{ij} s_i s_j$. As the Ising sping variable takes discrete values, the modularity maximisation becomes a combinatorial problem. To simplify the computation, the algorithm relaxes the assumption of discreteness and allows s_i to take real values, under the constraint of a "spherical model", i.e. $\sum_i s_i^2 = n$, that is $-\sqrt{n} \leq s_i \leq \sqrt{n}$.

The maximisation problem becomes:

$$maximise_s Q = s^T B s \quad s.t. \left||s|\right|_2 = 1$$

Which is a spectral matching problem, where the global optimum corresponds to the leading eigenvector of matrix B. The solution of the maximisation problem is provided by the derivative of the Lagrangian function.

The Louvain method. The Louvain Method (Blondel *et al.*, 2008) is a multi-level aggregation technique based on modularity optimization. It consists of two phases: *i)* it locally optimizes modularity and observes the potential gain generated by moving one node from its original community to another; *ii)* it aggregates nodes belonging to different communities. The two steps are applied repeatedly and sequentially. The first run typically results in smaller communities, while subsequent ones generate bigger ones as an outcome of the aggregation process. The Louvain method algorithm is highly efficient, mainly due to the fact that the potential modularity gains generated in phase one are easily computed as:

In the undirected case, the gain of modularity is easily computed as:

$$\Delta Q = \left[\frac{\sum_{in} + d_i^C}{2m} - \left(\frac{\sum_{tot} + d_i}{2m}\right)^2\right] - \left[\frac{\Sigma_{in}}{2m} - \left(\frac{\Sigma_{tot}}{2m}\right)^2 - \left(\frac{d_i}{2m}\right)^2\right] = \frac{d_i^2}{2m} - \frac{\sum_{tot} \cdot d_i}{2m^2}$$

where d_i^C is the degree of agent i in community C; Σ_{in} is the number of links belonging to community C, while Σ_{tot} is the number of links globally incident to community C. The algorithm runs up to maximal modularity is found.

Detecting key players. This step requires the punctual and explicit identification of actors exerting such a significant influence that their removal may cause a drop of cohesion or even a collapse of the network. The problem of influential agents has been widely discussed in literature: link deletion approaches (Valente and Fujimoto, 2010) are similar to node removal techniques (Borgatti, 2006), but they conceptually differ. While the former is exploring changes in cohesion as effect of manipulation of edges, the latter focuses on the consequences of modifications at node level.

I computed fragmentation centrality, which measures how fragmented the network becomes as effect of a node removal. The metric is mathematically expressed as:

$$F_i = 1 - \frac{\sum_{j,k\neq i} d_{jk}^{-1}}{d \cdot (n-1)(n-2)}$$

where d_{jk} is equal to the shortest path between nodes two nodes j and k once node i has been removed; d is the maximal of d_{jk}^{-1}. I obtained the set of key players that are crucial in not altering cohesion of the graph.

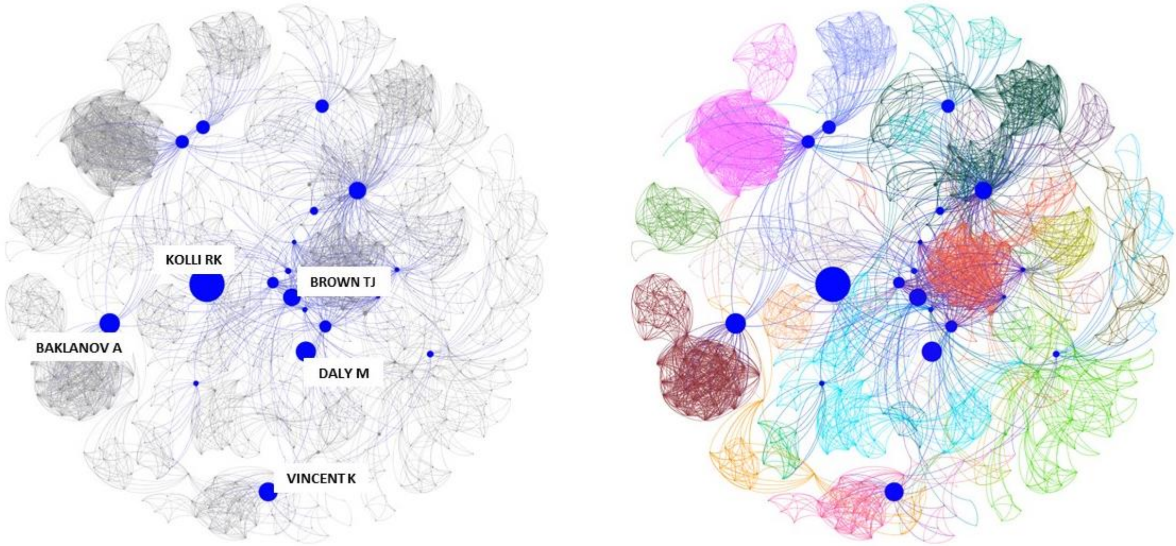


Figure 1.11S | Identification of key players in the network of individual scholars and their position within communities

I evaluated the performance of the four community detection algorithms by comparing their modularity score (Table 1.5S). The algorithms generate different community sizes and heterogeneous number of partitions. The top performer is the Louvain Method.

Table 1.5S | Comparison between community detection algorithms and their modularity scores

Algorithm	Communities	Modularity
Newman-Girvan	21	0.8313877
Greedy community	16	0.7897702
Spectral community	17	0.7905254
Louvain method	19	0.8395771

Results

Table 1.6S | Top 20 authors ranked per productivity (#articles)

Author	Score
Buontempo C.	13
Hewitt C.	11
Doblas-Reyes F.	9
Dessai S.	8
Lowe R.	7
Rodò X.	6
Thomson M.C.	6
Vaughan C.	6
Golding, N.	5
Guido Z.	5
Jacob D.	5
Winarto Y.T.	5
Bruno Soares M.	4
Dunstone N.	4
Kumar A.	4
Mason S.	4
Ray A.J.	4
Scaife A.A.	4
Tall A.	4
Troccoli A.	4

The most productive authors are ranked on the number of published articles in the sample. Hence, productivity is a simple metric of quantity. Authors are also ranked according to their centrality score (Table 1.7S), as derived from the Principal Component Analysis (PCA) of the available centrality measures. The score reflects the contribution of each agent to the first five dimensions. These explain approximately 86% of the total variance of the sample, which was deemed a significant threshold. Distance between scholars is progressively reduced along the ranking.

Table 1.7S | Top 20 authors ranked per centrality

Author	Score
Buontempo, C.	5.059
Kumar A.	1.692
Wintzer J.	1.256
Hewitt C.	1.153
Webb R.S.	1.091
Schulz J.	0.999
Kjellström E.	0.715
Jack C.	0.710
Zebiak S.E.	0.640
Brönnimann S.	0.639
Jourdain S.	0.615
Ray A.J.	0.614
Brown T.J.	0.613
Doblas-Reyes F.	0.597
Blaschek M.	0.539
Dahlgren P.	0.539
Vidard A.	0.538
Haimberger L.	0.537

Weaver A.	0.537
Valente M.A.	0.536

Table 1.8S | Top 20 institutions per centrality score

Affiliation	Score
Columbia University	4.358
University of Reading	3.687
University of Oxford	1.476
Desert Research Inst.	1.422
University of East Anglia	1.404
University of Helsinki	1.234
Observatori de l'Ebre	1.128
University of Florida	0.899
University of Chile	0.852
Barcelona Supercomputing Center	0.850
Sorbonne Université	0.838
University of Belgrade	0.837
Karlsruhe Institute of Technology	0.803
Spanish Meteorological Agency	0.792
Pacific Marine Environmental Laboratory	0.792
Izaña Atmospheric Research Center	0.788
Physikalisch-Meteorologisches Observatorium Davos	0.788
National Observatory of Athens	0.788
Max Planck Institut for Meteorologie	0.788
Naval Research Laboratory	0.786

Computation of the bridging properties at author and institution level offers a new perspective on the power of nodes included in the sample. The ranking provided below are the top 20 agents based on their role in reducing fragmentation in the network. These are the "brokers" of the graph: they reduce distances and facilitate the flow of information and knowledge.

Table 1.9S | Set of key authors

Author	Score
Kolli R.K.	0.773
Baklanov A.	0.756
Daly M.	0.756
Vincent K.	0.754
Brown T.J.	0.753
Buontempo C.	0.752
Grimmond C.S.B.	0.748
Jacob D..	0.747
Schulz J.	0.747
Kumar A.	0.746
Ray A.J..	0.745
Soubeyroux J-M	0.741
Jack C.	0.740
Vaughan C.	0.739
Vautard R.	0.738
Hewitt C.	0.738
Kjellström E.	0.737
Coughlan de Perez E.	0.737
Guido Z.	0.736

Zebiak S.E.	0.736

Table 1.10S | Set of key institutions

Affiliation	Score
University of Nairobi	0.605
Joint Research Centre	0.600
Met Office	0.599
Institució Catalana de Recerca i Estudis Avançats	0.592
National Center for Atmospheric Research	0.591
Desert Research Institute	0.590
University of Reading	0.590
NOAA	0.590
University of Chile	0.589
Royal Belgian Institute for Space Aeronomy	0.588
ECMWF	0.588
Columbia University	0.588
University of Leeds	0.588
Swedish Meteorological and Hydrological Institute	0.587
University of Helsinki	0.586
University of Oxford	0.586
Barcelona Supercomputing Center	0.586
Royal Netherlands Meteorological Institute	0.586
London School of Hygiene and Tropical Medicine	0.586
Deutscher Wetterdienst	0.586

Country-network

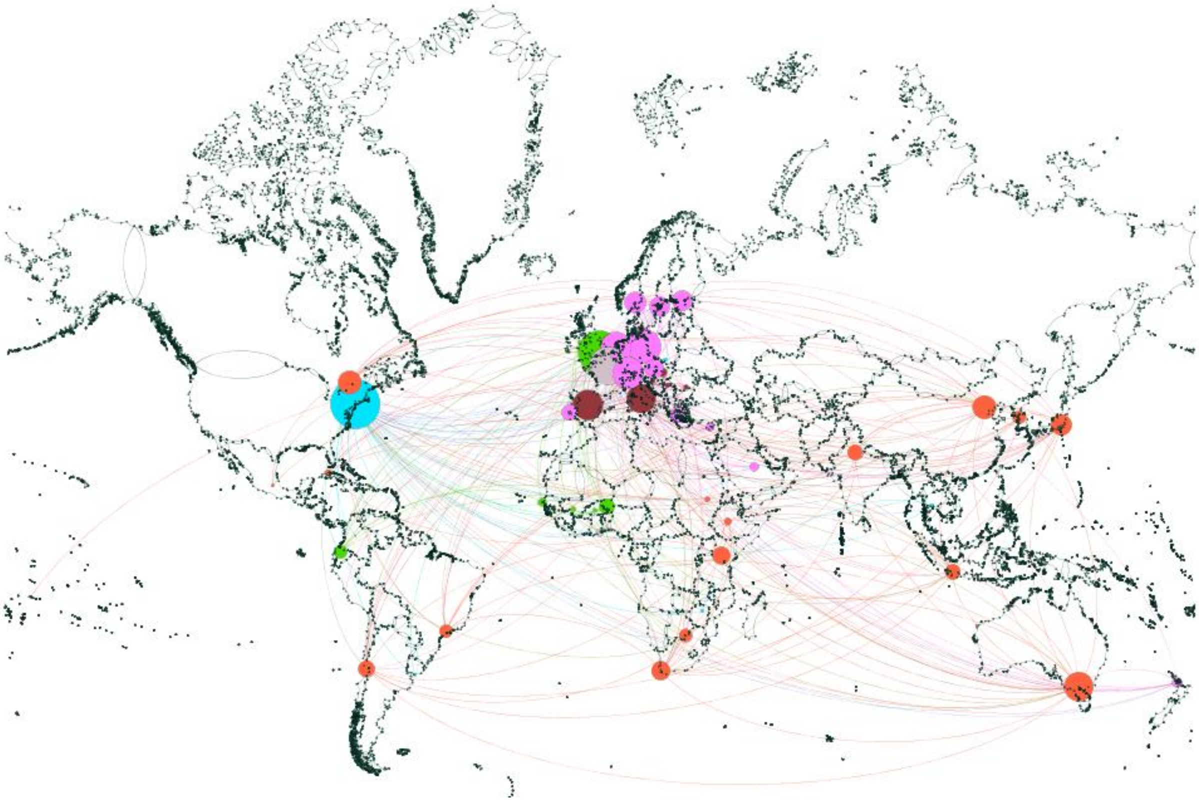


Figure 1.14S | Centrality as derived from the PCA. Different colors correspond to different clusters as extracted from the Louvain Method

Table 1.11S | Set of top central countries

Country	Score
USA	44
United Kingdom	38
France	33
Germany	30
Switzerland	28
Spain	27
The Netherlands	27
Italy	26
Australia	26
China	21
Canada	21
Norway	19
Japan	19
Sweden	18
Finland	17
South Africa	17
Austria	16
Kenya	15
Chile	14
Portugal	14

References

Agneessens, F., Borgatti, S. P. and Everett, M. G. (2017) 'Geodesic based centrality: Unifying the local and the global', *Social Networks*. North-Holland, 49, pp. 12–26. doi: 10.1016/J.SOCNET.2016.09.005.

Al-garadi, M. A., Varathan, K. D. and Ravana, S. D. (2017) 'Identification of influential spreaders in online social networks using interaction weighted K-core decomposition method', *Physica A: Statistical Mechanics and its Applications*. North-Holland, 468, pp. 278–288. doi: 10.1016/J.PHYSA.2016.11.002.

Alexander, M. and Dessai, S. (2019) 'What can climate services learn from the broader services literature?', *Climatic Change*. Springer Netherlands, pp. 1–17. doi: 10.1007/s10584-019-02388-8.

Alvarez-Hamelin, I. *et al.* (2005) 'k-core decomposition: a tool for the visualization of large scale networks', *arxiV*. Available at: https://arxiv.org/pdf/cs/0504107.pdf (Accessed: 10 May 2018).

Amissah-Arthur, A. (2003) 'Targeting Climate Forecasts for Agricultural Applications in Sub-Saharan Africa: Situating Farmers in User-Space', *Climatic Change*. Kluwer Academic Publishers, 58(1/2), pp. 73–92. doi: 10.1023/A:1023462613213.

Archambault, É. and Gagné, É. V. (2004) *The Use of Bibliometrics in the Social Sciences and Humanities*. Available at: www.science-metrix.com (Accessed: 22 January 2018).

Aria, M. and Cuccurullo, C. (2017) 'bibliometrix: An R-tool for comprehensive science mapping analysis', *Journal of Informetrics*. Elsevier, 11(4), pp. 959–975. doi: 10.1016/J.JOI.2017.08.007.

Ashtiani, M. *et al.* (2017) 'Selection of most relevant centrality measures: A systematic survey on protein-protein interaction networks', *bioRxiv*. doi: 10.1101/149492.

Ball, R. (2017) *Introduction to bibliometrics : new development and trends*. Chandos Publishing, an imprint of Elsevier. Available at: https://books.google.it/books?hl=it&lr=&id=wrlvDgAAQBAJ&oi=fnd&pg=PP1&dq=limits+of+bibliometrics&ots=RSac8RnVVa&sig=8xMxCVy-n7A2Ohh7CcJ-XcZfN2Y#v=onepage&q=limits of bibliometrics&f=false (Accessed: 7 June 2018).

Barabasi, A.-L. (2016) *Network Science*. 4th edn. Cambridge: Cambridge University Press. Available at: http://barabasi.com/f/622.pdf (Accessed: 18 January 2019).

Baronchelli, A. (2018) 'The emergence of consensus: a primer', *Royal Society of Open Science*, 5, p. 172189. doi: 10.1098/rsos.172189.

Barron, E. J. (2001) 'A climate services vision: First steps toward the future', *Board on Atmospheric Sciences and Climate*.

Becker, J., Brackbill, D. and Centola, D. (2017) 'Network dynamics of social influence in the wisdom of crowds.', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 114(26), pp. E5070–E5076. doi: 10.1073/pnas.1615978114.

Belter, C. W. (2015) 'Bibliometric indicators: opportunities and limits.', *Journal of the Medical Library Association*. Medical Library Association, 103(4), pp. 219–21. doi: 10.3163/1536-5050.103.4.014.

Blondel, V. D. *et al.* (2008) 'Fast unfolding of communities in large networks', *Journal of Statistical Mechanics: Theory and Experiment*. Available at: https://arxiv.org/pdf/0803.0476.pdf (Accessed: 5 April 2018).

Boccaletti, S. *et al.* (2006) 'Complex networks: Structure and dynamics', *Physics Reports*, 424, pp. 175–308. doi: 10.1016/j.physrep.2005.10.009.

Boldi, P. and Vigna, S. (2014) 'Axioms for Centrality', *Internet Mathematics*, 10(3–4), pp. 222–262. doi: 10.1080/15427951.2013.865686.

Borgatti, S. P. (2006) 'Identifying sets of key players in a social network', *Comput Math Organiz Theor*, 12, pp. 21–34. doi: 10.1007/s10588-006-7084-x.

Borgatti, S. P. *et al.* (2009) 'Network analysis in the social sciences.', *Science*. American Association for the Advancement of Science, 323(5916), pp. 892–5. doi: 10.1126/science.1165821.

Borgatti, S. P. and Everett, M. G. (2006) 'A Graph-theoretic perspective on centrality', *Social Networks*. North-Holland, 28(4), pp. 466–484. doi: 10.1016/J.SOCNET.2005.11.005.

Brandes, U., Borgatti, S. P. and Freeman, L. C. (2016) 'Maintaining the duality of closeness and betweenness centrality', *Social Networks*. North-Holland, 44, pp. 153–159. doi: 10.1016/J.SOCNET.2015.08.003.

Brandes, U., Erlebach, T. and Gesellschaft für Informatik. (2005) *Network analysis: methodological foundations*. Springer. Available at: https://books.google.it/books?id=VIMSPCIafakC&pg=PA38&lpg=PA38&dq=closeness+vitality&source=bl&ots=cEIBjAt3Ab&sig=_eSJi8JG7CpO7VW0miBQY1jzk-I&hl=it&sa=X&ved=0ahUKEwii-YHO2PjaAhWjF5oKHQlbAJIQ6AEIaTAI#v=onepage&q=closeness vitality&f=false (Accessed: 9 May 2018).

Bremer, S. and Meisch, S. (2017) 'Co-production in climate change research: reviewing different perspectives', *Wiley Interdisciplinary Reviews: Climate Change*. John Wiley & Sons, Ltd, 8(6), p. e482. doi: 10.1002/wcc.482.

Broadus, R. N. (1987) 'Toward a definition of "bibliometrics"', *Scientometrics*. Kluwer Academic Publishers, 12(5–6), pp. 373–379. doi: 10.1007/BF02016680.

Brooks, M. S. (2013) 'Accelerating Innovation in Climate Services: The 3 E's for Climate Service Providers', *Bulletin of the American Meteorological Society*. American Meteorological Society, 94(6), pp. 807–819. doi: 10.1175/BAMS-D-12-00087.1.

Bruno Soares, M., Alexander, M. and Dessai, S. (2017) 'Sectoral use of climate information in Europe: A synoptic overview', *Climate Services*. Elsevier B.V. doi: 10.1016/j.cliser.2017.06.001.

Bruno Soares, M. and Buontempo, C. (2019) 'Challenges to the sustainability of climate services in Europe', *Wiley Interdisciplinary Reviews: Climate Change*. John Wiley & Sons, Ltd, p. e587. doi: 10.1002/wcc.587.

Buizza, R. *et al.* (2018) 'The EU-FP7 ERA-CLIM2 Project Contribution to Advancing Science and Production of Earth System Climate Reanalyses', *Bulletin of the American Meteorological Society*, 99(5), pp. 1003–1014. doi: 10.1175/BAMS-D-17-0199.1.

Buontempo, C. *et al.* (2017) 'What have we learnt from EUPORIAS climate service prototypes?', *Climate Services*. Elsevier B.V. doi: 10.1016/j.cliser.2017.06.003.

Campitelli, M. G. *et al.* (2013) 'Lobby index as a network centrality measure', *Physica A*, 392, pp. 5511–5515. Available at: https://ac.els-cdn.com/S0378437113005839/1-s2.0-S0378437113005839-main.pdf?_tid=f4c2b4f4-a53e-4ff9-931d-e6d7aa67a0a5&acdnat=1525971168_1269b15f183fd17f9886a213e2d75e14 (Accessed: 10 May 2018).

Castellano, C., Fortunato, S. and Loreto, V. (2009) 'Statistical physics of social dynamics', *Reviews of Modern Physics*. American Physical Society, 81(2), pp. 591–646. doi: 10.1103/RevModPhys.81.591.

Chen, D.-B. *et al.* (2013) 'Identifying Influential Nodes in Large-Scale Directed Networks: The Role of Clustering', *PLoS ONE*, 8(10). doi: 10.1371/journal.pone.0077455.

Chin, C.-S. and Samanta, M. P. (2003) 'Global snapshot of a protein interaction network-a percolation based approach.', *Bioinformatics*, 19(18), pp. 2413–9. Available at: http://www.ncbi.nlm.nih.gov/pubmed/14668225 (Accessed: 10 May 2018).

Christel, I. *et al.* (2018) 'Introducing design in the development of effective climate services', *Climate Services*. Elsevier, 9, pp. 111–121. doi: 10.1016/J.CLISER.2017.06.002.

Cobo, M. J. *et al.* (2011) 'An approach for detecting, quantifying, and visualizing the evolution of a research field: A practical application to the Fuzzy Sets Theory field', *Journal of Informetrics*.

Elsevier, 5(1), pp. 146–166. doi: 10.1016/J.JOI.2010.10.002.
Cohen, P. J. *et al.* (2016) ‘Understanding adaptive capacity and capacity to innovate in social-ecological systems: Applying a gender lens’, *Ambio*. 2016/11/22. Springer Netherlands, 45(Suppl 3), pp. 309–321. doi: 10.1007/s13280-016-0831-4.
Crucitti, P., Latora, V. and Porta, S. (2006) ‘Centrality in networks of urban streets’, *Chaos*. doi: 10.1063/1.2150162.
Cueno, M. E. and Imai, K. (2018) ‘Network analytics approach towards identifying potential antivirulence drug targets within the Staphylococcus aureus staphyloxanthin biosynthetic network’, *Archives of Biochemistry and Biophysics*, 645, pp. 81–86. doi: 10.1016/j.abb.2018.03.010.
Damm, A. *et al.* (2019) ‘The market for climate services in the tourism sector – An analysis of Austrian stakeholders’ perceptions’, *Climate Services*. Elsevier. doi: 10.1016/J.CLISER.2019.02.001.
Dangalchev, C. (2006a) ‘Residual closeness in networks’, *Physica A: Statistical Mechanics and its Applications*. North-Holland, 365(2), pp. 556–564. doi: 10.1016/J.PHYSA.2005.12.020.
Dangalchev, C. (2006b) ‘Residual closeness in networks’, *Physica A: Statistical Mechanics and its Applications*. North-Holland, 365(2), pp. 556–564. doi: 10.1016/J.PHYSA.2005.12.020.
Das, K., Samanta, S. and Pal, M. (2018) ‘Study on centrality measures in social networks: a survey’, *Social Network Analysis and Mining*. Springer Vienna, 8(1), p. 13. doi: 10.1007/s13278-018-0493-2.
Dekker, M. M. *et al.* (2018) ‘Characteristics and development of European cyclones with tropical origin in reanalysis data’, *Climate Dynamics*. Springer Berlin Heidelberg, 50(1–2), pp. 445–455. doi: 10.1007/s00382-017-3619-8.
Deng, S.-P., Zhu, L. and Huang, D.-S. (2016) ‘Predicting Hub Genes Associated with Cervical Cancer through Gene Co-Expression Networks’, *IEEE/ACM Transactions on Computational Biology and Bioinformatics*, 13(1). doi: 10.1109/TCBB.2015.2476790.
Dinku, T. *et al.* (2014) ‘Bridging critical gaps in climate services and applications in africa’, *Earth Perspectives*. SpringerOpen, 1(1), p. 15. doi: 10.1186/2194-6434-1-15.
Directorate-General for Research and Innovation, E. C. (2015) ‘European roadmap for Climate Services’, in. Brussels: European Commission.
Dokas, I. M. *et al.* (2017) ‘Information systems for crisis response and management in Mediterranean Countries’, in *4th International Conference, ISCRAM*, p. 221. Available at: https://books.google.it/books?id=N_M4DwAAQBAJ&pg=PA7&lpg=PA7&dq=EPC+-+Edge+Percolated+Component&source=bl&ots=TqUQLhsmQv&sig=hauV79ek5mtCwdLpj4-ZcrRSnGg&hl=it&sa=X&ved=0ahUKEwi2pf71pP3aAhWJB8AKHX3hCPwQ6AEIczAN#v=onepage&q=EPC - Edge Percolated Com (Accessed: 11 May 2018).
Estrada, E. and Rodríguez-Velázquez, J. A. (2005) ‘Subgraph centrality in complex networks’, *Physical Review E*. American Physical Society, 71(5), p. 056103. doi: 10.1103/PhysRevE.71.056103.
De Felice, M. *et al.* (2019) ‘Scoping the potential usefulness of seasonal climate forecasts for solar power management’, *Renewable Energy*. Pergamon, 142, pp. 215–223. doi: 10.1016/J.RENENE.2019.03.134.
Ferreira, F. F. *et al.* (2016) ‘Behavior of surface water in the Pacific and Atlantic during the period 1982 2014 [Comportamento das águas superficiais nos oceanos Pacifico e Atlântico durante o período de 1982 a 2014]’, *Revista Brasileira de Meteorologia*. Sociedade Brasileira de Meteorologia, 31(3), pp. 366–373. doi: 10.1590/0102-778631320160050.
Fletcher, J. M. and Wennekers, T. (2018) ‘From Structure to Activity: Using Centrality Measures to Predict Neuronal Activity’, *International Journal of Neural Systems*, 28(175001316). doi: 10.1142/S0129065717500137.
Ford, J. D., Knight, M. and Pearce, T. (2013) ‘Assessing the “usability” of climate change research for decision-making: A case study of the Canadian International Polar Year’, *Global Environmental Change*. Pergamon, 23(5), pp. 1317–1326. doi:

10.1016/J.GLOENVCHA.2013.06.001.
Fouss, F., Saerens, M. and Shimbo, M. (2016) *Algorithms and models for network data and link analysis*. Cambridge. Cambridge University Press. Available at: http://www.cambridge.org/it/academic/subjects/computer-science/knowledge-management-databases-and-data-mining/algorithms-and-models-network-data-and-link-analysis?format=HB&isbn=9781107125773#04wVUgC83RAvRHUW.97 (Accessed: 10 May 2018).
Goddard, L. *et al.* (2010) ‘Providing Seasonal-to-interannual climate information for risk management and decision-making’, in *Procedia Environmental Sciences*. Elsevier B.V., pp. 81–101. doi: 10.1016/j.proenv.2010.09.007.
Granovetter, M. S. (1973) ‘The Strength of Weak Ties’, *American Journal of Sociology*, 78(6), pp. 1360–1380. Available at: https://www.jstor.org/stable/pdf/2776392.pdf?refreqid=excelsior%3A1d122a8b7669a66335f747ac6af96d1a (Accessed: 1 October 2018).
Hage, P. and Harary, F. (1995) ‘Eccentricity and centrality in networks’, *Social Networks*. North-Holland, 17(1), pp. 57–63. doi: 10.1016/0378-8733(94)00248-9.
Han, X. *et al.* (2017) ‘Emergence of communities and diversity in social networks.’, *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 114(11), pp. 2887–2891. doi: 10.1073/pnas.1608164114.
Haunschild, R., Bornmann, L. and Marx, W. (2016) ‘Climate Change Research in View of Bibliometrics’, *PLOS ONE*. Edited by W. Glanzel. Public Library of Science, 11(7), p. e0160393. doi: 10.1371/journal.pone.0160393.
Hernández, J. M. and Mieghem, P. Van (2011) ‘Classification of graph metrics’. Available at: https://www.nas.ewi.tudelft.nl/people/Piet/papers/TUDreport20111111_MetricList.pdf (Accessed: 10 May 2018).
Hewitt, C., Mason, S. and Walland, D. (2012) ‘The Global Framework for Climate Services’, *Nature Climate Change*. Nature Research, 2(12), pp. 831–832. doi: 10.1038/nclimate1745.
Hubbell, C. H. (1965) ‘An Input-Output Approach to Clique Identification An Input-Output Approach to Clique Identification *’, *Sociometry*, 28(4), pp. 377–399. Available at: http://www.jstor.org/stable/2785990 (Accessed: 11 May 2018).
van den Hurk, B. J. J. M. *et al.* (2016) ‘Improving predictions and management of hydrological extremes through climate services’, *Climate Services*. Elsevier B.V., 1, pp. 6–11. doi: 10.1016/j.cliser.2016.01.001.
Ivanov, S. E., Gorlushkina, N. N. and Ivanova, L. N. (2018) ‘Multi-parametric centrality method for graph network models’, in *AIP Conference Proceedings*, p. 020043. doi: 10.1063/1.5032005.
Johnson, P. T. J., de Roode, J. C. and Fenton, A. (2015) ‘Why infectious disease research needs community ecology.’, *Science*. NIH Public Access, 349(6252), p. 1259504. doi: 10.1126/science.1259504.
Jones, L. *et al.* (2017) ‘Constraining and enabling factors to using long-term climate information in decision-making’, *Climate Policy*. Taylor and Francis Ltd., 17(5), pp. 551–572. doi: 10.1080/14693062.2016.1191008.
Joyce, K. E. *et al.* (2010) ‘A New Measure of Centrality for Brain Networks’, *PLoS ONE*, 5(8). doi: 10.1371/.
Kabir, M. *et al.* (2017) ‘Properties of genes essential for mouse development’, *PloS One*. doi: 10.1371/journal.pone.0178273.
Kalinka, A. T. and Tomancak, P. (2011) ‘linkcomm: an R package for the generation, visualization, and analysis of link communities in networks of arbitrary size and type’, *Bioinformatics*. Oxford University Press, 27(14), pp. 2011–2012. doi: 10.1093/bioinformatics/btr311.
Kirchhoff, C. J., Lemos, M. C. and Kalafatis, S. (2015) ‘Narrowing the gap between climate

science and adaptation action: The role of boundary chains', *Climate Risk Management*, 9, pp. 1–5. doi: 10.1016/j.crm.2015.06.002.

Kleinberg, J. M. (1998) 'Authoritative Sources in a Hyperlinked Environment *'. Available at: https://www.cs.cornell.edu/home/kleinber/auth.pdf (Accessed: 10 May 2018).

Konstantinidis, K., Papadopoulos, S. and Kompatsiaris, Y. (2017) 'Exploring Twitter communication dynamics with evolving community analysis', *PeerJ Computer Science*. PeerJ Inc., 3, p. e107. doi: 10.7717/peerj-cs.107.

Korn, A., Schubert, A. and Telcs, A. (2009) 'Lobby index in networks', *Physica A: Statistical Mechanics and its Applications*. North-Holland, 388(11), pp. 2221–2226. doi: 10.1016/J.PHYSA.2009.02.013.

Krippendorff, K. (2004) *Content analysis : an introduction to its methodology*. SAGE Publications. Available at: https://books.google.it/books?id=q657o3M3C8cC&pg=PA3&hl=it&source=gbs_toc_r&cad=4#v=onepage&q&f=false (Accessed: 21 September 2018).

Kumar Surendra Kumar, S. and Kretschmer, H. (2008) 'Collaboration in Research Productivity in Oil Seed Research Institutes of India', in Kretschmer, H. and Havemann, F. (eds) *4th International Conference on Webometrics, Infometrics and Scientometrics*. Berlin. Available at: http://www.collnet.de/Berlin-2008/KumarWIS2008cir.pdf (Accessed: 9 April 2018).

L.D, D. B. and Raj, E. D. (2017) 'Flocking based evolutionary computation strategy for measuring centrality of online social networks', *Applied Soft Computing*. Elsevier, 58, pp. 495–516. doi: 10.1016/J.ASOC.2017.04.047.

Larivière, V. *et al.* (2013) 'Bibliometrics: Global gender disparities in science', *Nature*, 504(7479), pp. 211–213. doi: 10.1038/504211a.

Latora, V. and Marchiori, M. (2001) 'Efficient Behavior of Small-World Networks', *Physical Review Letters*, 87(89). doi: 10.1103/PhysRevLett.87.198701.

Lechthaler, F. and Vinogradova, A. (2017) 'The climate challenge for agriculture and the value of climate services: Application to coffee-farming in Peru', *European Economic Review*. Elsevier B.V., 99, pp. 5–30. doi: 10.1016/j.euroecorev.2017.06.006.

Li, H. *et al.* (2018) 'Current Flow Group Closeness Centrality for Complex Networks', *arxiV*. Available at: https://arxiv.org/pdf/1802.02556.pdf (Accessed: 10 May 2018).

Li, W. and Schuurmans, D. (2011) 'Modular Community Detection in Networks', in *Proceedings of the Twenty-Second International Joint Conference on Artificial Intelligence*. Available at: https://www.ijcai.org/Proceedings/11/Papers/231.pdf (Accessed: 21 January 2019).

Li, Y., Giuliani, M. and Castelletti, A. (2017) 'A coupled human-natural system to assess the operational value of weather and climate services for agriculture', *Hydrology and Earth System Sciences*. Copernicus GmbH, 21(9), pp. 4693–4709. doi: 10.5194/hess-21-4693-2017.

Lin, C.-Y. *et al.* (2008) 'Hubba: hub objects analyzer—a framework of interactome hubs identification for network biology', *Nucleic Acids Research*. Oxford University Press, 36(suppl_2), pp. W438–W443. doi: 10.1093/nar/gkn257.

Lindberg, F. *et al.* (2018) 'Urban Multi-scale Environmental Predictor (UMEP): An integrated tool for city-based climate services', *Environmental Modelling and Software*. Elsevier Ltd, 99, pp. 70–87. doi: 10.1016/j.envsoft.2017.09.020.

Liu, K. and Yan, X. (2018) 'Current-flow efficiency of networks', *Physica A: Statistical Mechanics and its Applications*. North-Holland, 492, pp. 463–471. doi: 10.1016/J.PHYSA.2017.10.039.

Ma, A., Mondragón, R. J. and Latora, V. (2015) 'Anatomy of funded research in science.', *Proceedings of the National Academy of Sciences of the United States of America*. National Academy of Sciences, 112(48), pp. 14760–5. doi: 10.1073/pnas.1513651112.

Martín-Martín, A., Orduna-Malea, E. and Delgado López-Cózar, E. (2018) 'A novel method for depicting academic disciplines through Google Scholar Citations: The case of Bibliometrics', *Scientometrics*, 114(3), pp. 1251–1273. doi: 10.1007/s11192-017-2587-4doi.org/10.1007/s11192-

017-2587-4.

Mehlhorn, H. and Schreiber, F. (2013) 'Small-World Property BT - Encyclopedia of Systems Biology', in Dubitzky, W. et al. (eds). New York, NY: Springer New York, pp. 1957–1959. doi: 10.1007/978-1-4419-9863-7_2.

Miles, E. L. *et al.* (2006) 'An approach to designing a national climate service', *Proceedings of the National Academy of Sciences of the United States of America*, 103(52), pp. 19616–19623. doi: 10.1073/pnas.0609090103.

Milo, R. *et al.* (2002) 'Network motifs: simple building blocks of complex networks.', *Science*. American Association for the Advancement of Science, 298(5594), pp. 824–7. doi: 10.1126/science.298.5594.824.

Newman, M. E. J. (2003) 'The Structure and Function of Complex Networks', *Society for Industrial and Applied Mathematics*, 45(2), pp. 167–256. Available at: http://www.siam.org/journals/ojsa.php (Accessed: 24 September 2018).

Newman, M. E. J. (2004) 'Fast algorithm for detecting community structure in networks', *Physical Review E*. American Physical Society, 69(6), p. 066133. doi: 10.1103/PhysRevE.69.066133.

Newman, M. E. J. (2013) 'Spectral methods for community detection and graph partitioning', *PHYSICAL REVIEW E*, 88, p. 42822. doi: 10.1103/PhysRevE.88.042822.

Newman, M. E. J. and Girvan, M. (2004a) 'Finding and evaluating community structure in networks', *Physical Review E*, 69(2), p. 026113. doi: 10.1103/PhysRevE.69.026113.

Newman, M. E. J. and Girvan, M. (2004b) 'Finding and evaluating community structure in networks', *Physical Review E*. American Physical Society, 69(2), p. 026113. doi: 10.1103/PhysRevE.69.026113.

Nie, T. *et al.* (2016) 'Using mapping entropy to identify node centrality in complex networks', *Physica A: Statistical Mechanics and its Applications*. North-Holland, 453, pp. 290–297. doi: 10.1016/J.PHYSA.2016.02.009.

Nishi, A. *et al.* (2015) 'Inequality and visibility of wealth in experimental social networks', *Nature*. Nature Publishing Group, 526(7573), pp. 426–429. doi: 10.1038/nature15392.

Opsahl, T., Agneessens, F. and Skvoretz, J. (2010) 'Node centrality in weighted networks: Generalizing degree and shortest paths', *Social Networks*. North-Holland, 32(3), pp. 245–251. doi: 10.1016/J.SOCNET.2010.03.006.

Otte, E. and Rousseau, R. (2002) 'Social network analysis: a powerful strategy, also for the information sciences', *Journal of Information Science*. Sage PublicationsSage CA: Thousand Oaks, CA, 28(6), pp. 441–453. doi: 10.1177/016555150202800601.

'Package "sna": Tools for Social Network Analysis' (2016) *CRAN project*. Available at: http://www.statnet.org (Accessed: 11 May 2018).

Pal, S. K., Kundu, S. and Murthy, C. A. (2014) 'Centrality Measures, Upper Bound, and Influence Maximization in Large Scale Directed Social Networks', *Fundamenta Informaticae*. IOS Press, 130(3), pp. 317–342. doi: 10.3233/FI-2014-994.

Qi, X. *et al.* (2012) 'Laplacian centrality: A new centrality measure for weighted networks', *Information Sciences*. Elsevier, 194, pp. 240–253. doi: 10.1016/J.INS.2011.12.027.

Qi, X. *et al.* (2013) 'Terrorist Networks, Network Energy and Node Removal: A New Measure of Centrality Based on Laplacian Energy', *Social Networking*, 2, pp. 19–31. doi: 10.4236/sn.2013.21003.

Del Rio, G., Koschützki, D. and Coello, G. (2009) 'How to identify essential genes from molecular networks?', *BMC Systems Biology*, 3(102). doi: 10.1186/1752-0509-3-102.

Ruhnau, B. (2000) 'Eigenvector-centrality — a node-centrality?', *Social Networks*. North-Holland, 22(4), pp. 357–365. doi: 10.1016/S0378-8733(00)00031-9.

Scardoni, G., Petterlini, M. and Laudanna, C. (2009) 'Analyzing biological network parameters with CentiScaPe', *Bioinformatics*. Oxford University Press, 25(21), pp. 2857–2859. doi: 10.1093/bioinformatics/btp517.

Scott, D. J., Lemieux, C. J. and Malone, L. (2011) ‘Climate services to support sustainable tourism and adaptation to climate change’, *Climate Research*, 47(1–2), pp. 111–122. doi: 10.3354/cr00952.

Scott, D. and Lemieux, C. (2010) ‘Weather and climate information for tourism’, in *Procedia Environmental Sciences*. Elsevier B.V., pp. 146–183. doi: 10.1016/j.proenv.2010.09.011.

Stigter, K. (2008) ‘Policy support for capacity building in weather and climate services focused on agriculture’, *Journal of Agrometeorology*, 10(2), pp. 107–111. Available at: https://www.scopus.com/inward/record.uri?eid=2-s2.0-78049411266&partnerID=40&md5=04e4fdda8ee4bdd5717337e3bf2fa172.

Street, R. *et al.* (2015) ‘A European research and innovation Roadmap for Climate Services’, *European Commission*.

Suebsombut, P. *et al.* (2017) ‘The using of bibliometric analysis to classify trends and future directions on “smart farm”’, in *2017 International Conference on Digital Arts, Media and Technology (ICDAMT)*. IEEE, pp. 136–141. doi: 10.1109/ICDAMT.2017.7904950.

Takes, F. W. and Kosters, W. A. (2013) ‘Computing the Eccentricity Distribution of Large Graphs’, *Algorithms*, 6, pp. 100–118. doi: 10.3390/a6010100.

Thomson Reuters (2008) *Using Bibliometrics: A Guide to Evaluating Research Performance with Citation Data*. Available at: http://ips.clarivate.com/m/pdfs/325133_thomson.pdf (Accessed: 22 January 2018).

Tian, Y., Wen, C. and Hong, S. (2008) ‘Global scientific production on GIS research by bibliometric analysis from 1997 to 2006’, *Journal of Informetrics*, 2, pp. 65–74. doi: 10.1016/j.joi.2007.10.001.

Troccoli, A. *et al.* (2018) ‘Creating a proof-of-concept climate service to assess future renewable energy mixes in Europe: An overview of the C3S ECEM project’, *Advances in Science and Research*, 15, pp. 191–205. doi: 10.5194/asr-15-191-2018.

Tsakas, N. (2017) ‘On Decay Centrality’, *Cornell University*. Available at: https://arxiv.org/pdf/1604.05582.pdf (Accessed: 9 May 2018).

Valente, T. W. and Fujimoto, K. (2010) ‘Bridging: Locating Critical Connectors in a Network.’, *Social networks*. NIH Public Access, 32(3), pp. 212–220. doi: 10.1016/j.socnet.2010.03.003.

Vaughan, C. *et al.* (2016) ‘Identifying research priorities to advance climate services’, *Climate Services*. Elsevier B.V., 4, pp. 65–74. doi: 10.1016/j.cliser.2016.11.004.

Vaughan, C. and Dessai, S. (2014) ‘Climate services for society: Origins, institutional arrangements, and design elements for an evaluation framework’, *Wiley Interdisciplinary Reviews: Climate Change*. Wiley-Blackwell, 5(5), pp. 587–603. doi: 10.1002/wcc.290.

Vaughan, C. and Hewitt, C. (2018) ‘Surveying Climate Services: What Can We Learn from a Bird’s-Eye View?’, *American Meteorological Society*. doi: 10.1175/WCAS-D-17-0030.1.

Vogel, C. and O’Brien, K. (2006) ‘Who can eat information? Examining the effectiveness of seasonal climate forecasts and regional climate-risk management strategies’, *Climate Research*, 33(1), pp. 111–122. doi: 10.3354/cr033111.

Wang, Y. *et al.* (2017) ‘Identifying Influential Spreaders on Weighted Networks Based on ClusterRank’, in *2017 10th International Symposium on Computational Intelligence and Design (ISCID)*. IEEE, pp. 476–479. doi: 10.1109/ISCID.2017.222.

Weaver, C. P. *et al.* (2013) ‘Improving the contribution of climate model information to decision making: the value and demands of robust decision frameworks’, *Wiley Interdisciplinary Reviews: Climate Change*. John Wiley & Sons, Ltd, 4(1), pp. 39–60. doi: 10.1002/wcc.202.

Webber, S. (2017) ‘Circulating climate services: Commercializing science for climate change adaptation in Pacific Islands’, *Geoforum*. Elsevier Ltd, 85, pp. 82–91. doi: 10.1016/j.geoforum.2017.07.009.

Webber, S. and Donner, S. D. (2017) ‘Climate service warnings: cautions about commercializing climate science for adaptation in the developing world’, *Wiley Interdisciplinary*

Reviews: Climate Change. Wiley-Blackwell, 8(1). doi: 10.1002/wcc.424.

White, C. J. *et al.* (2017) 'Potential applications of subseasonal-to-seasonal (S2S) predictions', *Meteorological Applications*. John Wiley and Sons Ltd, 24(3), pp. 315–325. doi: 10.1002/met.1654.

World Meteorological Organisation, W. (2009) 'Climate Knowledge for Action: A Global Framework for Climate Services –'. Available at: https://www.wmo.int/gfcs/sites/default/files/FAQ/HLT/HLT_FAQ_en.pdf (Accessed: 28 June 2017).

Youngblood, M. and Lahti, D. (2018) 'A bibliometric analysis of the interdisciplinary field of cultural evolution', *Palgrave Communications*. Nature Publishing Group, 4(1), p. 120. doi: 10.1057/s41599-018-0175-8.

Yu, H. *et al.* (2007) 'The Importance of Bottlenecks in Protein Networks: Correlation with Gene Essentiality and Expression Dynamics', *PLOS Computational Biology*. Available at: http://journals.plos.org/ploscompbiol/article/file?id=10.1371/journal.pcbi.0030059&type=printable (Accessed: 9 May 2018).

Zare-Farashbandi, F., Geraei, E. and Siamaki, S. (2014) 'Study of co-authorship network of papers in the Journal of Research in Medical Sciences using social network analysis.', *Journal of research in medical sciences : the official journal of Isfahan University of Medical Sciences*. Wolters Kluwer -- Medknow Publications, 19(1), pp. 41–6. Available at: http://www.ncbi.nlm.nih.gov/pubmed/24672564 (Accessed: 22 January 2018).

Zheng, Y. *et al.* (2017) 'Identification of hub genes involved in the development of hepatocellular carcinoma by transcriptome sequencing.', *Oncotarget*. Impact Journals, LLC, 8(36), pp. 60358–60367. doi: 10.18632/oncotarget.19483.

CHAPTER 2. SUPPLEMENTARY MATERIAL

Descriptive statistics

The database includes *New build* (3162), *Acquisition* (318) and *Refinancing* (129) projects. The dataset is dominated (96.1%) by small hydro facilities, while large hydro represents a small proportion of the financial transactions (3.9%). Within small hydro, 75.3% of the transactions is related to Run of River (RoR) facilities, which are typically smaller and less damaging to the environment. Also, RoR are cheaper than New Dams (16.7%) or Existing Dams (4.1%).

Network statistics

The topology of the debt and equity networks (Table 2.1S) have different characteristics with respect to the dispersion of their degree distributions (Figure 2.1S, quantified with coefficient of variation (CoV)). The dispersion in the degree distribution of the debt networks is high ($\gtrsim 2$) indicating the presence of hubs. The dispersion in the degree distribution of the equity networks (both weighted and unweighted) is closer to 1, indicating fewer/smaller hubs.

The computation of the global clustering coefficient and short average path length and their comparison with two random graphs reveal the presence of topological order and bicliques in the network. The global clustering coefficient of the network is high compared to the network under degree-preserving randomization (approx. x10), implying topological order that goes beyond hub structure i.e. community structure. The presence of a community structure is signaled by an average shortest path length lower than a random graph.

Table 2.1S | Topological network analysis

Average Shortest Path Length Random			Global Clustering Coefficient				
Empirical value	Rnd value	Z-score	Empirical value	Rnd value	Z-score	Rnd PD value	Z-score
7.6	9.6	-15	0.07	0.003	46	0.011	31

Figure 2.1S | Degree distribution

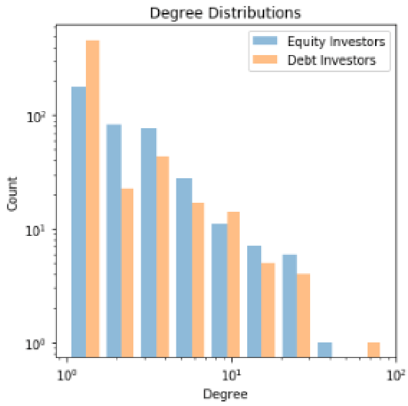


Figure 2.2aS | Equity network: distribution of investors' categories in the top countries per transaction

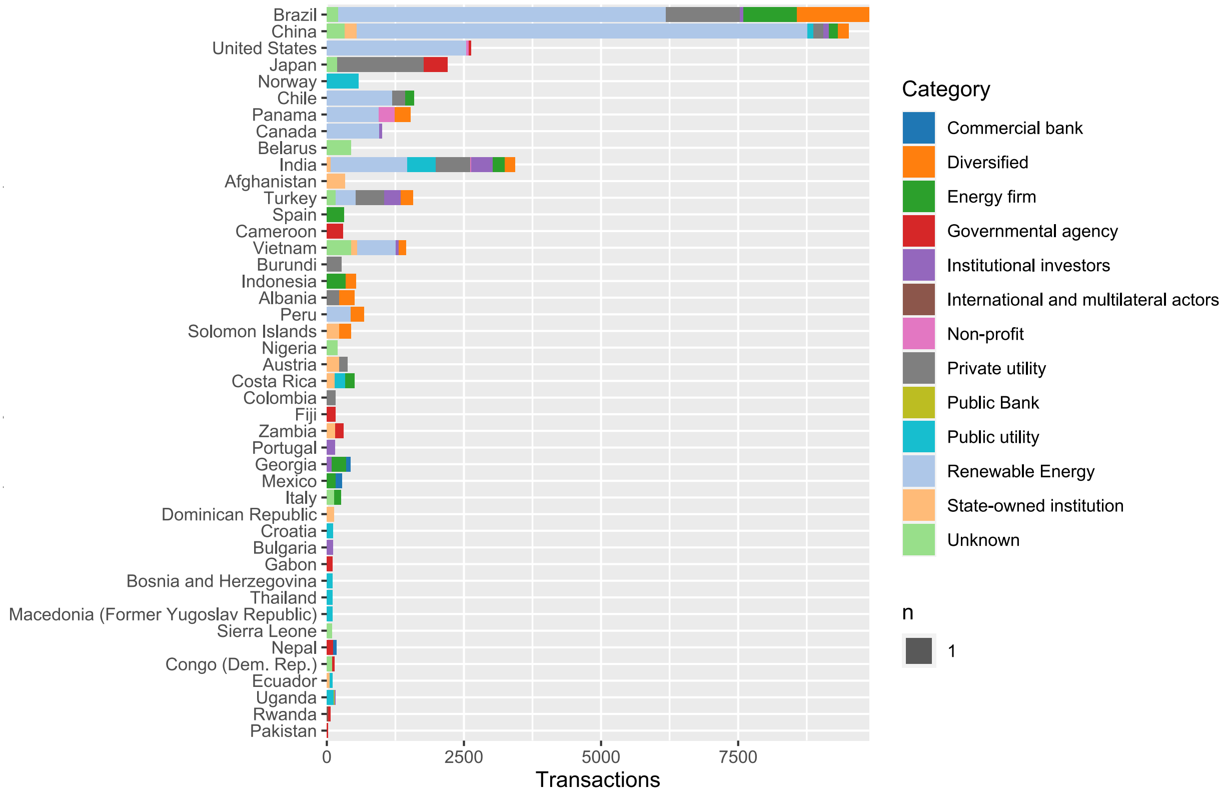
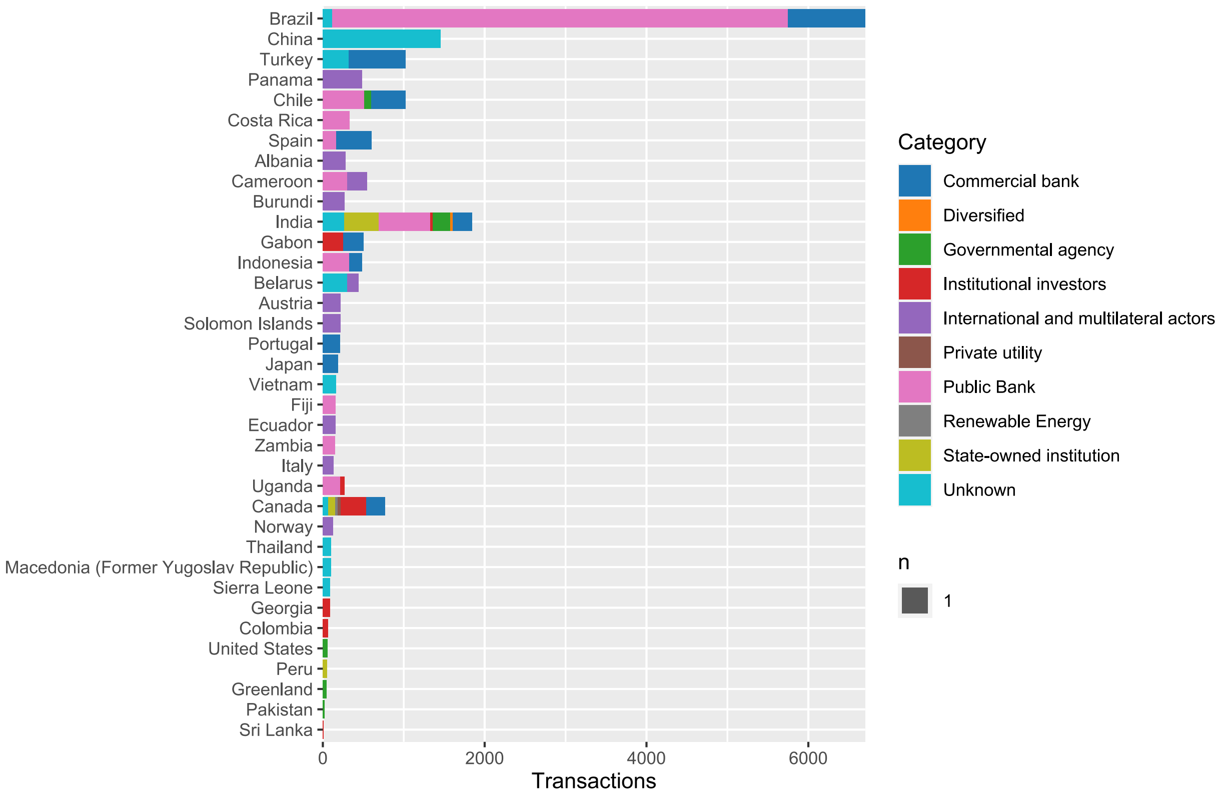


Figure 2.2bS | Debt network: distribution of investors' categories in the top countries per transaction



Community detection

The network's hierarchical structure is built using pairwise similarities between two links $e_{ik} and\ e_{jk}$ sharing node a node k. Similarity is obtained from the Jaccard coefficient:

$$S(e_{ik}, e_{jk}) = \frac{|n_+(i) \cap n_+(j)|}{|n_+(i) \cup n_+(j)|}$$

where $n_+(i)$ is the first-order neighborhood of node (i). Pairwise similarities are the seeds of a hierarchical dendrogram where branches describe communities with links occupying a unique position and nodes assigned to multiple clusters. The hierarchical dendrogram is then cut at the point where the partition density (D) is maximised. The partition density reveals the optimal number of communities since multiple cutting thresholds exist. It is computed at each level of the dendrogram, and it is based on the density of links within each community.

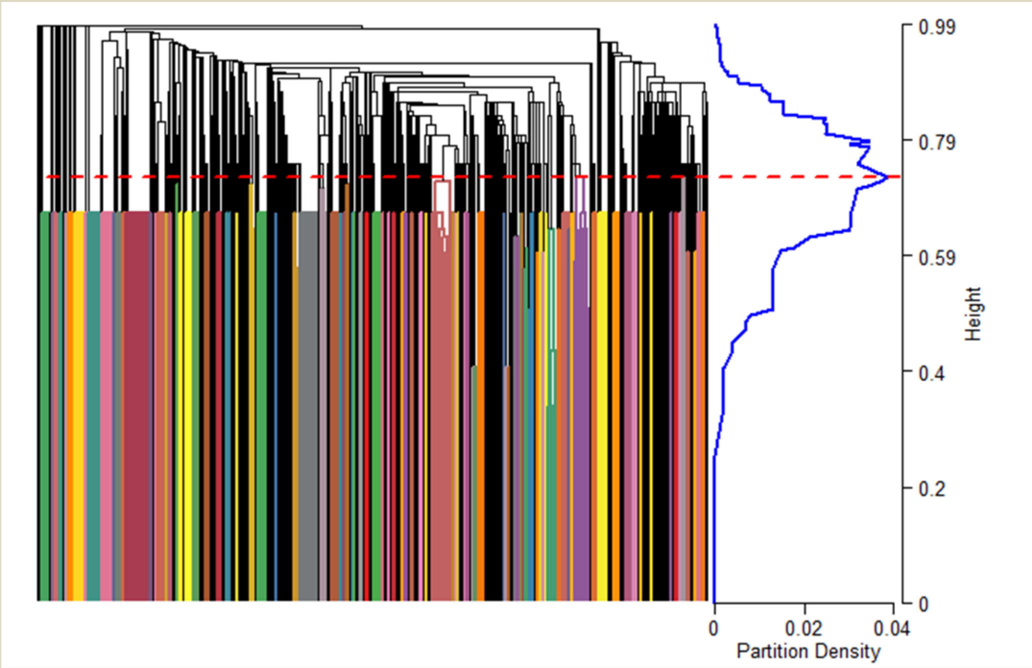


Figure 2.3S | The link communities partition and the partition density

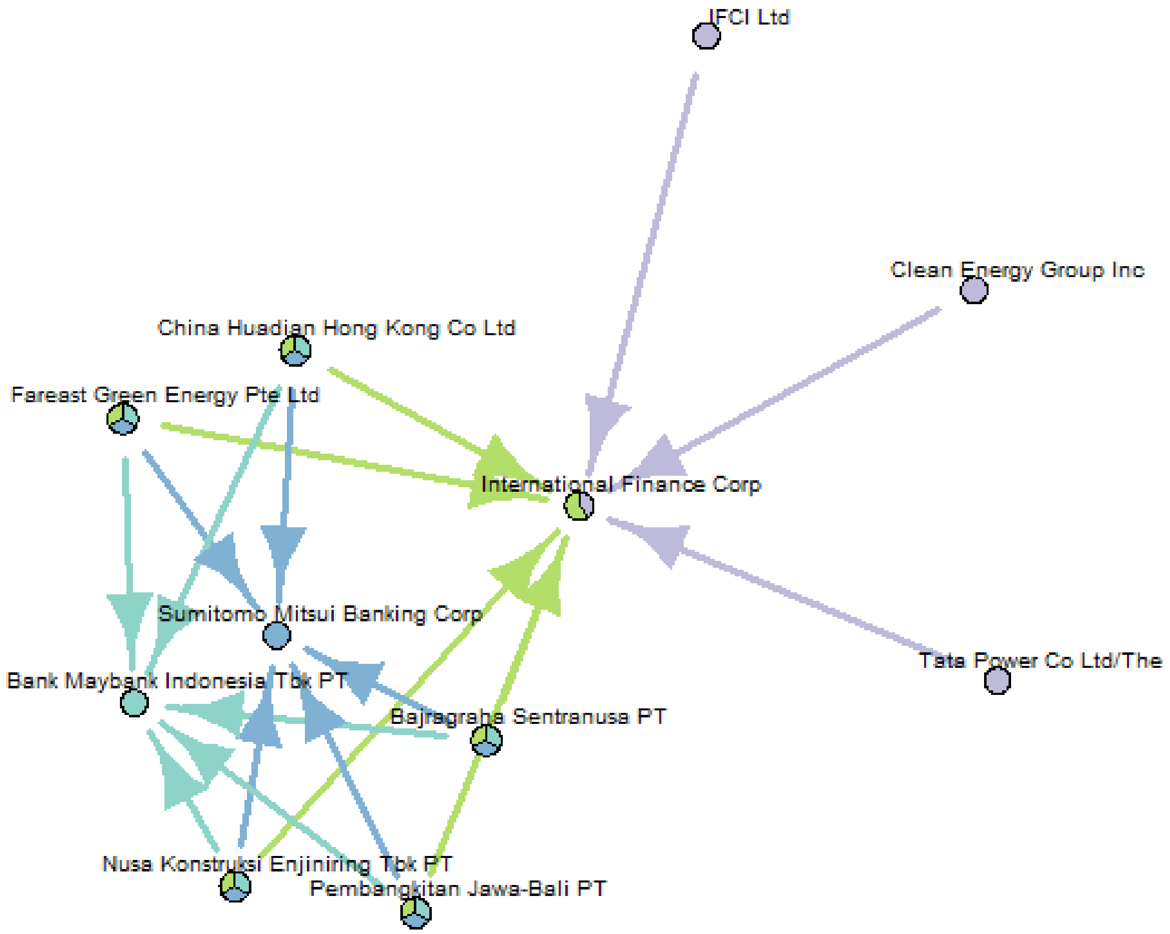


Figure 2.4S | Example of overlapping communities: the most central investor (IFC)

CHAPTER 3. SUPPLEMENTARY MATERIAL

The corpus of peer-reviewed publications: query details

The bibliometric database was compiled in November 2020 from Scopus. The query uses a combination of single and plural terminologies and aims at capturing the change in the scientific jargon. Existing studies surveyed the universe of climate change research (Callaghan et al., 2020; Grieneisen & Zhang, 2011; Haunschild et al., 2016) proving this approach has both limitations and advantages. Furthermore, a comprehensive query requires the researchers to appreciate the evolution of different terms across time and space. Expressions like “global warming” have been recently replaced by the broader “climate change”.

The query is restricted to the focus of the study: innovation. As such, it is not as broad as the ones used by previous works. The query is based on the following combination of keywords: (global warming” AND “innovation; “greenhouse gas effect” AND “innovation”; “climate change” AND “innovation”) in the title, abstract and paper keywords domain. The query leads to 6018 publications. After checking for duplicates with correspondence > 90% in the title and abstract. After cleaning, our bibliometric database includes 5556 records.

Table 3.1S| The Timeframe split of the peer-reviewed research

Years	Assessment Report
1979-1989	AR1
1990-1994	AR2
1995-2000	AR3
2001-2006	AR4
2007-2013	AR5
2014-2018	SR1.5
2019-2021	AR6

Table 3.2S | Research topics as derived from STM

	Topic	Key terms
1	The role of scientific research in advancing research for climate change	scienc, educ, univers, engin, knowledg, book, student
2	Product innovation: implications for	green, chain, procur, suppli, cleantech,

	sustainability	manufactur, award
3	Process innovation: focus on local actions in urban areas	innov, citi, urban, social, sustain, challeng, solut
4	Global challenges in innovation for climate change	global, world, problem, environment, challeng, human, econom
5	Smart solutions to face essential climate variables changes	weather, temperatur, season, extrem, rainfal, trend, precipit
6	Business innovations for climate change	industri, busi, sector, market, econom, compani, innov
7	Life-cycle assessments to identify the impact of products on climate change	build, eco, life, hous, cycl, lca, construct
8	Innovations in the transport sector to become climate-smart	transport, vehicl, fuel, emiss, air, pollut, electr
9	Improve health quality: mitigating the impacts of climate change	health, diseas, care, public, improv, popul, impact
10	Innovation to climate change in developing countries	develop, region, sustain, nation, countri, european, intern
11	Structural changes in materials and constructions due to climate change	structur, wood, concret, materi, design, mine, construct
12	MIXED	polici, innov, literatur, instrument, review, maker, environment
13	Adoption, diffusion and deployment of technological innovations for climate change	technolog, innov, develop, adopt, diffus, transfer, deploy
14	Addressing the human-nature complex interactions in agriculture	system, ecolog, natur, human, environment, complex, sustain
15	Blue and green infrastructures	land, forest, soil, rural, manag, area, ecosystem
16	Improved water resources management	water, manag, resourc, flood, increas, suppli, urban
17	Enabling innovative adaptation to reduce vulnerability and mitigate climate change risk	adapt, risk, resili, communiti, capac, vulner, strategi
18	Economic innovations to improve	cost, innov, price, trade, countri, effect, polici

	adaptation to climate change	
19	Low-carbon technologies use: focus on China	carbon, low, develop, china, industri, economi, innov
20	Electricity production through renewable energy sources	energi, renew, electr, power, effici, fossil, sourc
21	Innovations in models and approaches	model, scenario, assess, approach, base, futur, evalu
22	Biomass and bioproducts	bio, biomass, bioeconomi, biofuel, bioenergi, methan, biorefineri
23	Carbon capture storage technologies to reduce emissions	captur, ccs, greenhous, coal, kyoto, cap, gas
24	Marine conservation and innovations for coastal areas	coastal, ocean, marin, conserv, data, sea, monitor
25	Genetically-modified crops and innovations in the agricultural sector	crop, agricultur, food, soybean, farm, farmer, rice
26	Thermal efficient technologies from renewable technologies	heat, thermal, cool, solar, refriger, instal, photovolta
27	Governance in climate change innovation	subnat, govern, polit, actor, local, municip, state
28	Spatio-temporal evolution of climate technology innovation	speci, evolut, human, innov, late, shift, climat
29	Reducing conmption-based emissions: energy efficiency	emiss, consumpt, reduc, reduct, result, econom, effect
30	Transformational economic and technological processes	transit, transform, path, narrat, radic, regim, discours
31	Chemical and industrial innovations to face climate change	semiconductor, ion, solvent, nanotechnolog, metal, ceram, nano
32	Emerging evolution practices in climate change adaptation	studi, innov, practic, adopt, find, environment, factor
33	Climate services and climate data provision	inform, servic, data, network, space, smart, communic
34	Organizational innovations to enable transition to climate change	measur, respons, public, start, driven, develop, associ

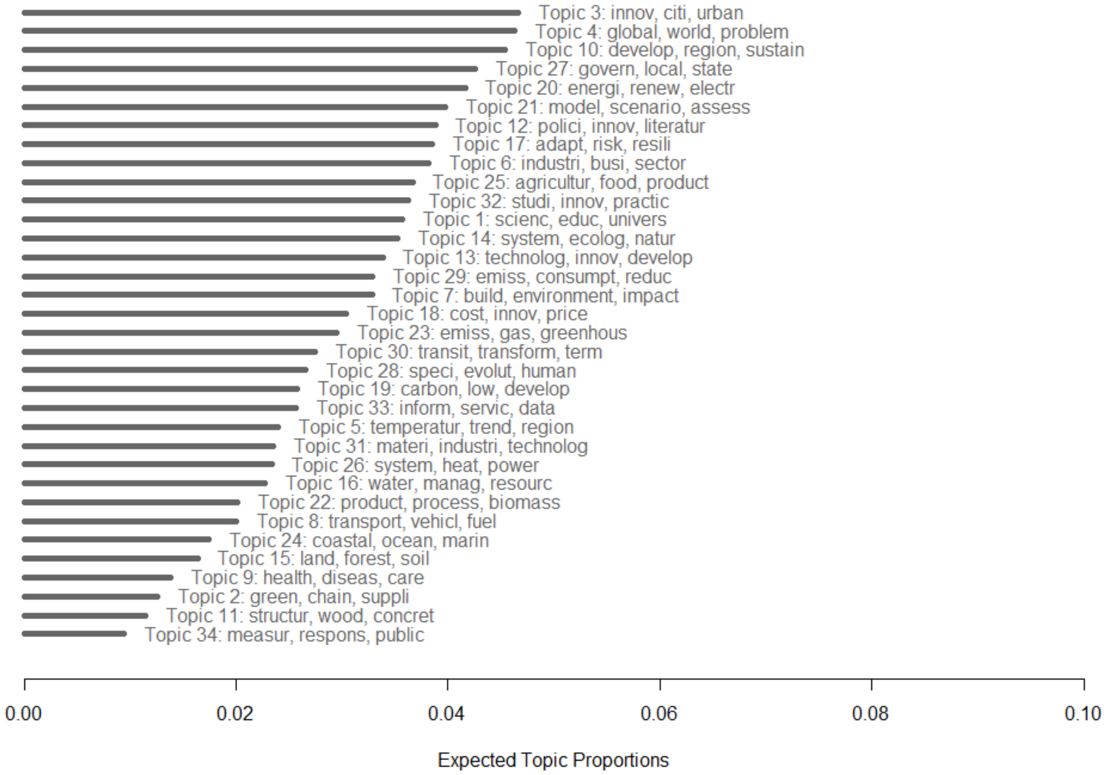
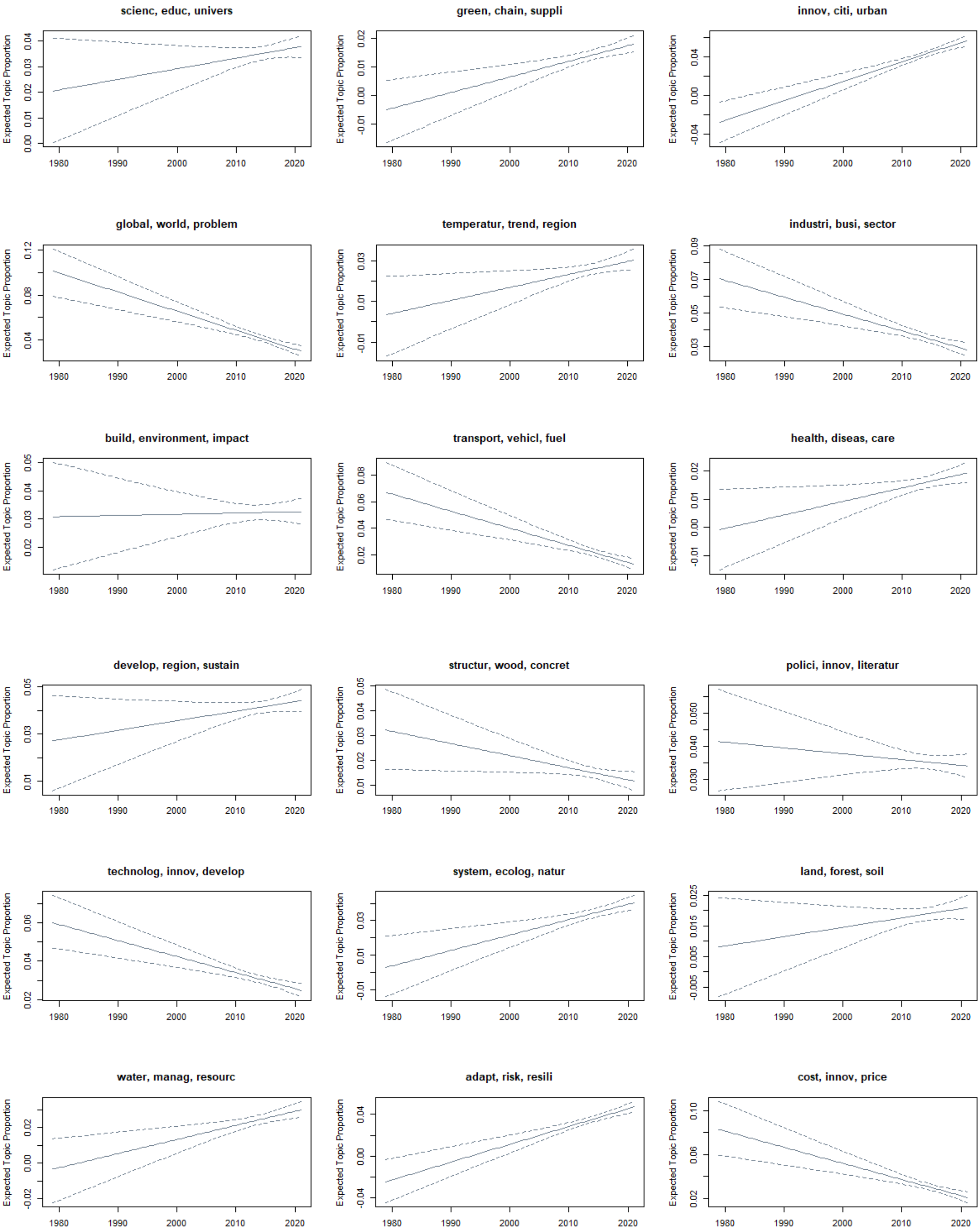


Figure 3.1S | Topic proportion across the whole timespan - research



scienc, educ, univers
green, chain, suppli
innov, citi, urban
global, world, problem
temperatur, trend, region
industri, busi, sector
build, environment, impact
transport, vehicl, fuel
health, diseas, care
develop, region, sustain
structur, wood, concret
polici, innov, literatur
technolog, innov, develop
system, ecolog, natur
land, forest, soil
water, manag, resourc
adapt, risk, resili
cost, innov, price
Expected Topic Proportion
1980
1990
2000
2010
2020

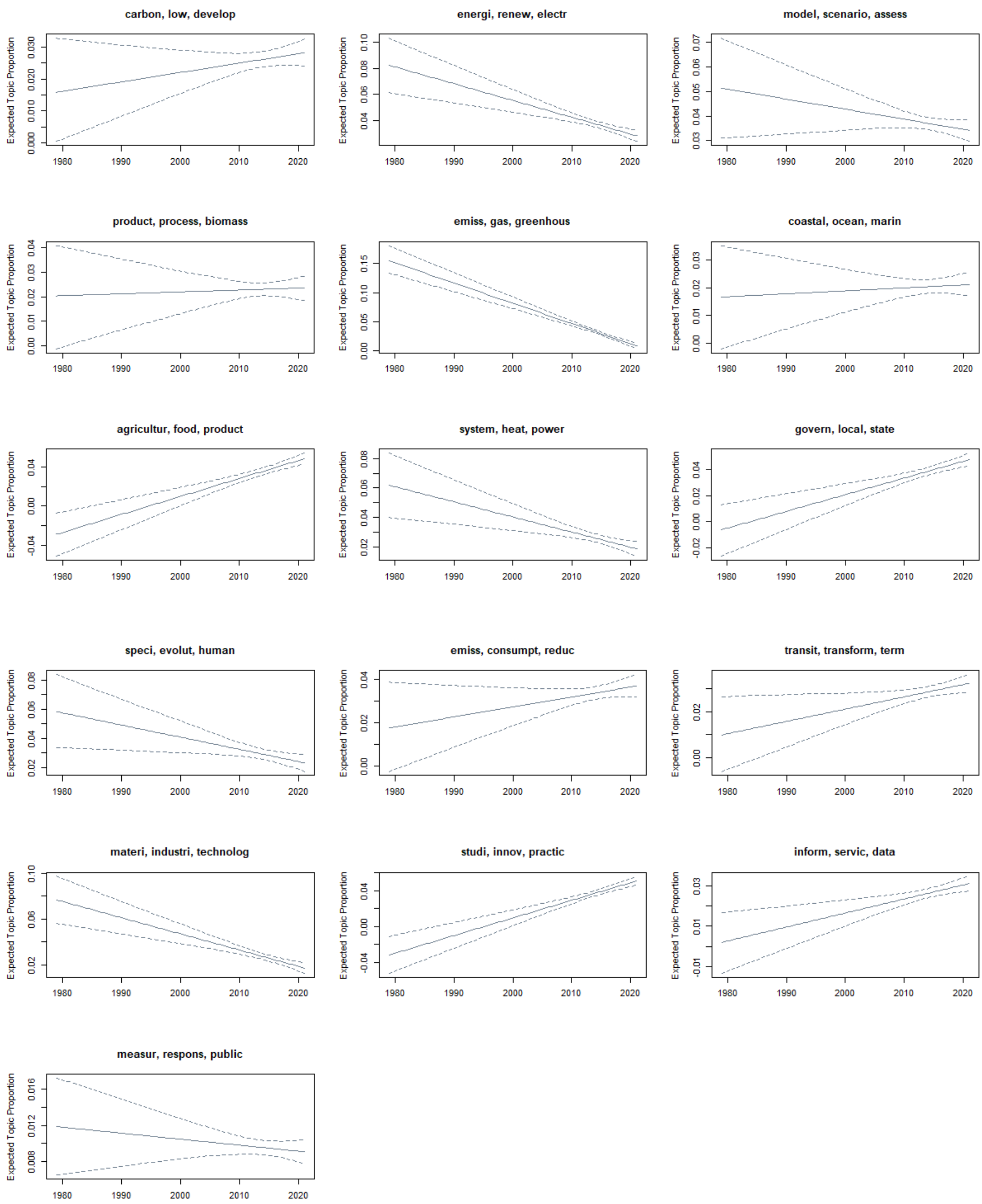


Figure 3.2S | Topics growth overtime - research

The corpus of EU funded projects: data collection details

The list of EU funded projects in all disciplines and subjects is derived from the European Commission Open data Portal in July 2020 and includes three framework programmes: FP6, FP7 and H2020. Projects of interest are selected by applying the same query used for the corpus of peer reviewed publications. The final dataset has 2067 projects.

Table 3.3S | Projects topics as derived from STM

	Topic	Key terms
1	Displaying and showcasing the advancements of EU research on climate innovation	research, train, institut, skill, scientif, knowledg, univers, host, expertis, scienc, collabor, project, develop, network, scientist, lead, work, transfer, intern, career
2	Citizen science and civil society engagement	green, chain, procur, suppli, cleantech, manufactur, award
3	Climate services	data, monitor, inform, observ, develop, servic, european, satellit, provid, system, user, use, remot, qualiti, sens, product, network, integr, oper, earth
4	Progresses in terrestrial carbon and water cycles	carbon, soil, cycl, global, ecosystem, flux, emiss, atmospher, terrestri, sink, process, effect, organ, veget, greenhous, import, understand, sourc, use, studi
5	Developing early-warning systems for freshwater ecosystems under climate stress	communiti, marin, effect, ecosystem, coral, temperatur, warm, global, chang, food, affect, fish, reef, level, function, environment, impact, web, organ, predict
6	Understanding the atmospheric circulation response to climate change	ocean, circul, atlant, atmospher, deep, variabl, sea, surfac, understand, observ, southern, physic, process, north, studi, global, transport, region, forc, import
7	Rethinking economics under changing climate conditions	research, polici, econom, analysi, theori, decis, transit, social, studi, system, project, empir, develop, object, uncertainti, model, propos, can, role, aim
8	Innovations for water and groundwater management	water, river, manag, resourc, qualiti, hydrolog, system, use, develop, also, basin, suppli, drink, area, demand, technolog, increas, project, groundwat, integr
9	Supportin European climate innvoation policies for adaptation and mitigation	polici, assess, impact, adapt, econom, develop, mitig, global, strategi, scenario, region, effect, european, option, integr, sector, project, level, cost, intern

10	Protecting biodiversity in the face of climate change	speci, popul, ecolog, evolutionari, rang, distribut, environment, adapt, project, genet, use, predict, respons, biodivers, pattern, effect, divers, habitat, studi, understand
11	Next generation technologies for industrail applications	develop, environment, technolog, use, engin, safeti, industri, applic, project, system, perform, treatment, techniqu, sustain, improv, reduc, structur, also, smes, impact
12	Fostering EU cooperation to tackle climate innovation	research, european, activ, programm, region, countri, project, nation, joint, cooper, develop, coordin, europ, fund, support, area, initi, intern, action, network
13	Improving energy efficiency and circular solutions in cities	energi, urban, citi, build, effici, system, use, plan, project, heat, consumpt, need, sustain, develop, technolog, renew, base, design, integr, demand
14	Understanding forest processes under a changing climate	forest, tree, tropic, fire, growth, manag, function, use, carbon, respons, understand, structur, studi, disturb, role, condit, trait, chang, dynam, drought
15	Knowledge, management and assessment of ecosystem services	ecosystem, biodivers, manag, ecolog, mediterranean, develop, marin, servic, conserv, use, scale, human, function, sustain, resourc, impact, chang, natur, knowledg, provid
16	IoT and technologies for electricity production	technolog, power, oper, system, industri, wind, energi, cost, infrastructur, deploy, project, increas, generat, develop, ship, grid, first, transport, time, need
17	Knowledge and assessment of extreme events	extrem, weather, event, impact, season, variabl, region, term, chang, drought, increas, understand, long, climat, forecast, condit, precipit, rainfal, high, monsoon
18	Climate-resistant crops and transformation in agriculture	plant, gene, molecular, genom, use, respons, adapt, mechan, genet, stress, root, temperatur, environ, regul, physiolog, understand, interact, project, chang, sequenc
19	Monitoring and checking the air quality and atmospheric state	atmospher, aerosol, air, cloud, pollut, qualiti, emiss, measur, process, chemistri, stratospher, radiat, effect, ozon, global, impact, studi, understand, observ, instrument

20	Market-ready new materials for energy efficiency	market, cost, solut, product, year, technolog, project, commerci, high, use, busi, can, materi, reduc, low, increas, save, develop, million, phase
21	MIXED	
22	Learning from the past: evolutionary dynamics under climate change	ocean, marin, chemic, organ, sediment, carbon, process, biolog, phytoplankton, understand, global, product, nutrient, use, cycl, earth, develop, propos, studi, microbi
23	Pathways for possible future accounting for ethnographic and anthropological insights	human, cultur, environment, project, social, global, understand, studi, polit, peopl, research, local, migrat, behaviour, environ, context, natur, africa, futur, can
24	Models and tools for carbon and GHG emissions	energi, fuel, emiss, transport, carbon, use, technolog, materi, effici, high, gas, electr, fossil, cell, reduct, propos, renew, storag, can, batteri
25	Flood risk assessments: early warning systems and tools	risk, flood, manag, hazard, coastal, assess, project, develop, disast, effect, area, natur, infrastructur, tool, transport, structur, process, damag, adapt, resili
26	Nature-based solutions for urban transition	servic, innov, develop, support, manag, sector, sustain, challeng, solut, base, user, stakehold, resili, busi, communiti, platform, market, provid, knowledg, build
27	Innovations in the agroforestry systems	agricultur, crop, food, product, sustain, system, improv, farm, breed, farmer, qualiti, use, secur, increas, develop, manag, genet, yield, european, effici
28	Resolving subglacial properties, hydrological networks and dynamic evolution of ice flows	ice, arctic, sea, glacier, sheet, polar, level, project, chang, melt, greenland, futur, region, antarct, use, understand, rise, mass, core, year
29	Bioenergy and agri-food solutions	product, food, industri, sustain, chain, resourc, base, suppli, effici, valu, bio, process, project, growth, market, increas, develop, biomass, wast, bioenergi
30	Anticipating climate change with improved Earth monitoring systems	model, system, predict, project, futur, scale, use, dynam, process, improv, simul, develop, earth, interact, result, coupl, uncertainti, integr, data, understand

31	Cost-effective solutions and tools to strengthen safety and health to climate-related risks	health, diseas, human, pathogen, pest, control, develop, invas, infect, virus, europ, increas, emerg, vector, exposur, risk, tool, effect, detect, anim
32	Paleoclimatology	past, record, chang, reconstruct, isotop, proxi, period, time, use, last, data, provid, studi, core, year, sediment, climat, temperatur, lake, warm
33	Land Use and Climate Change Attribution for biodiversity impact assessments	land, use, level, rise, contribut, develop, data, measur, first, futur, applic, bayesian, process, global, project, sea, assess, sub, model, one

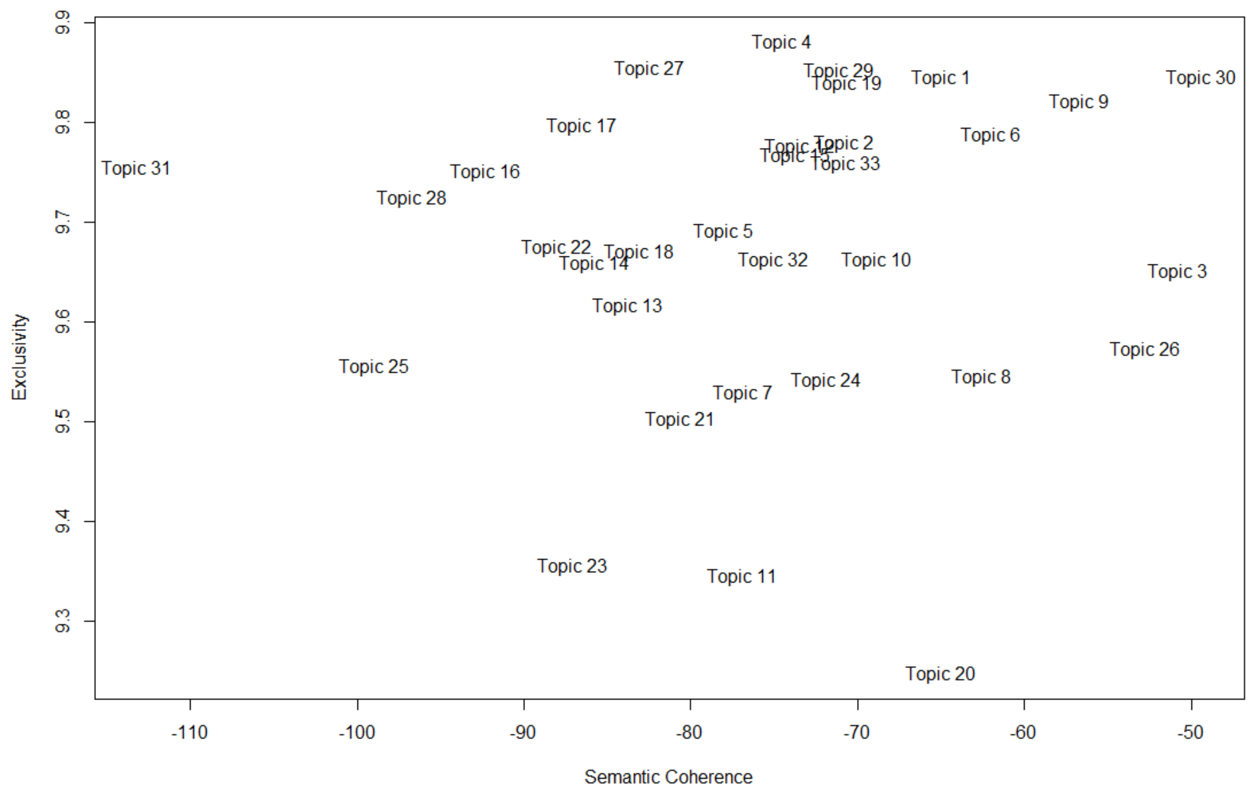


Figure 3.3S | Topic quality

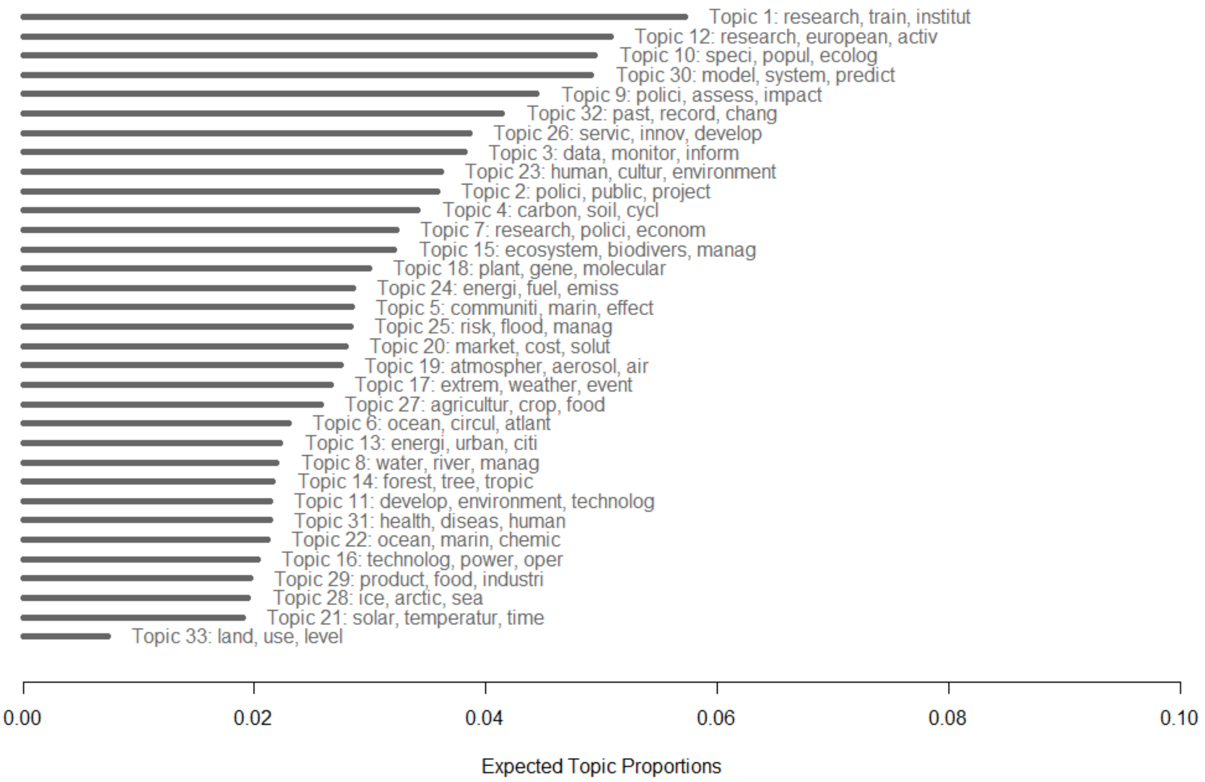
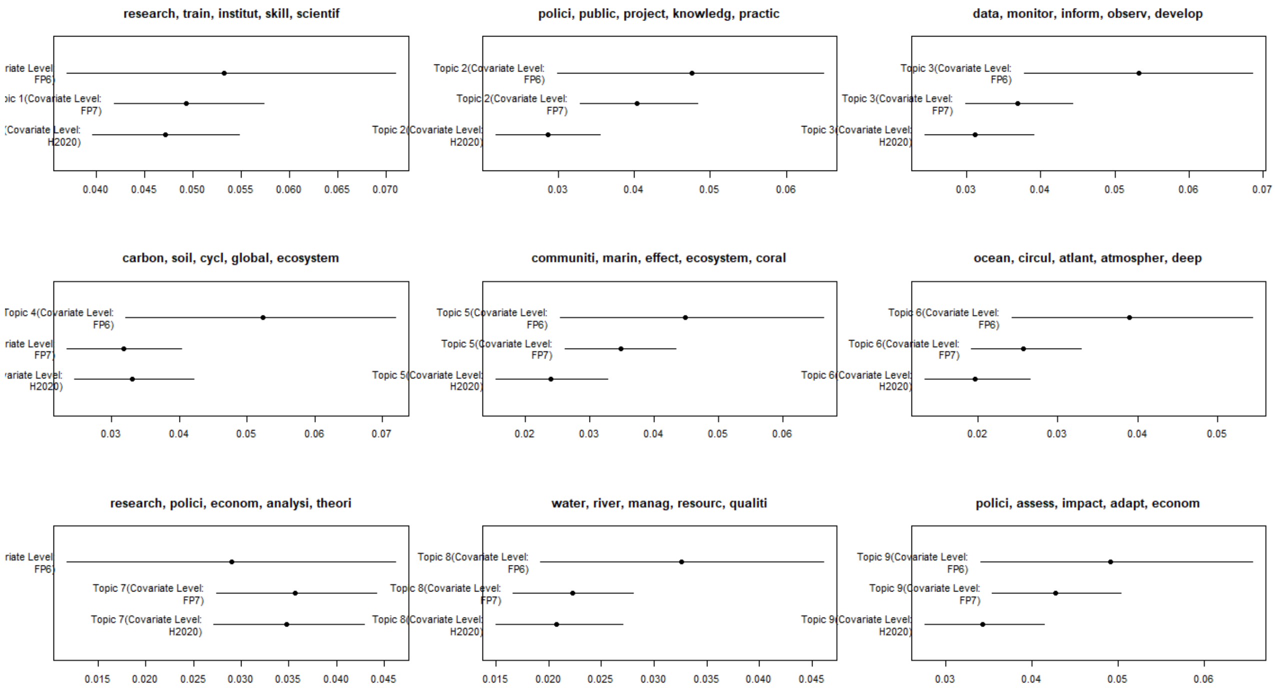
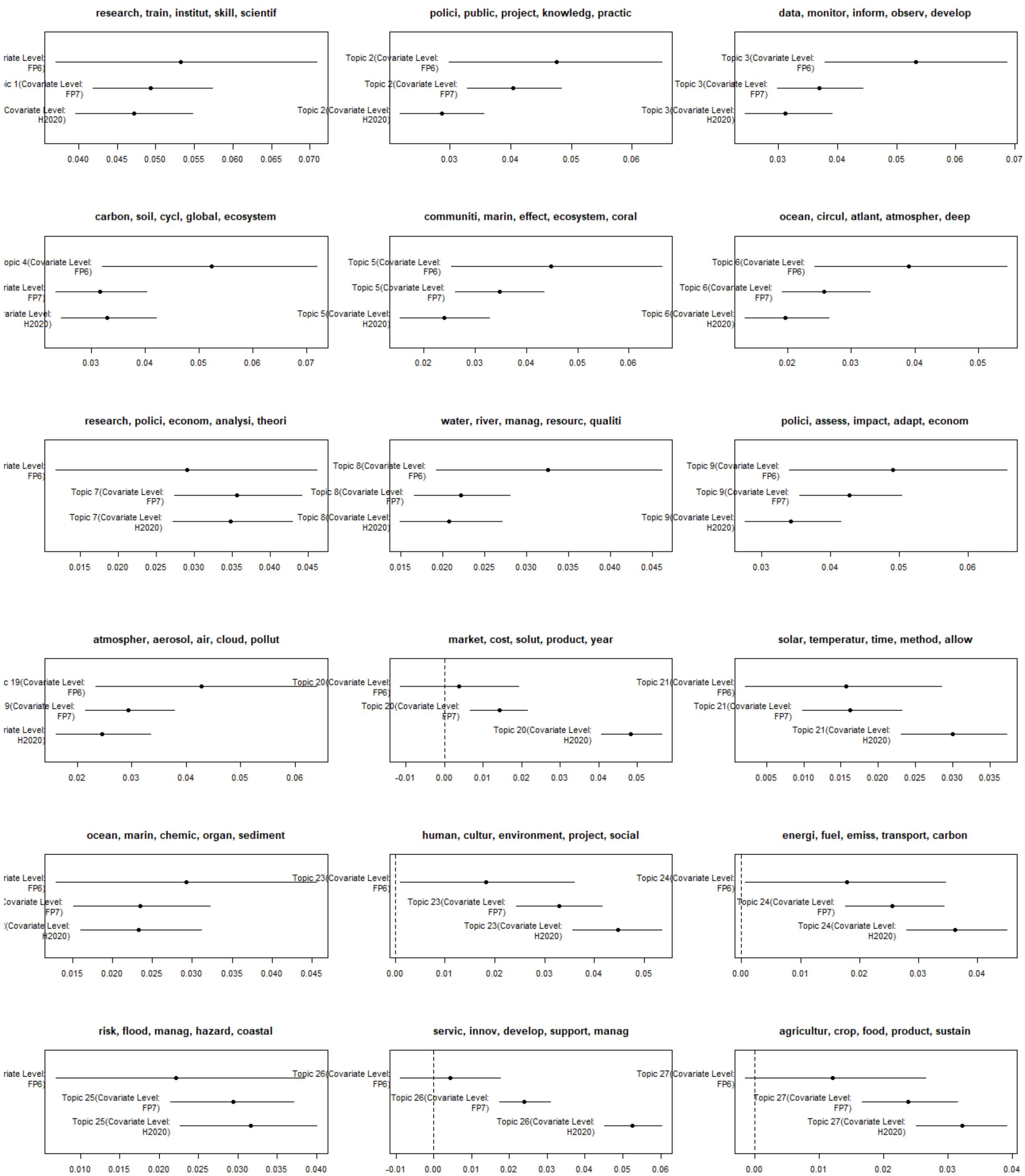


Figure 3.4S | Topic proportion across the whole timespan – projects




research, train, institut, skill, scientif
polici, public, project, knowledg, practic
data, monitor, inform, observ, develop
carbon, soil, cycl, global, ecosystem
communiti, marin, effect, ecosystem, coral
ocean, circul, atlant, atmospher, deep
research, polici, econom, analysi, theori
water, river, manag, resourc, qualiti
polici, assess, impact, adapt, econom
atmospher, aerosol, air, cloud, pollut
market, cost, solut, product, year
solar, temperatur, time, method, allow
ocean, marin, chemic, organ, sediment
human, cultur, environment, project, social
energi, fuel, emiss, transport, carbon
risk, flood, manag, hazard, coastal
servic, innov, develop, support, manag
agricultur, crop, food, product, sustain

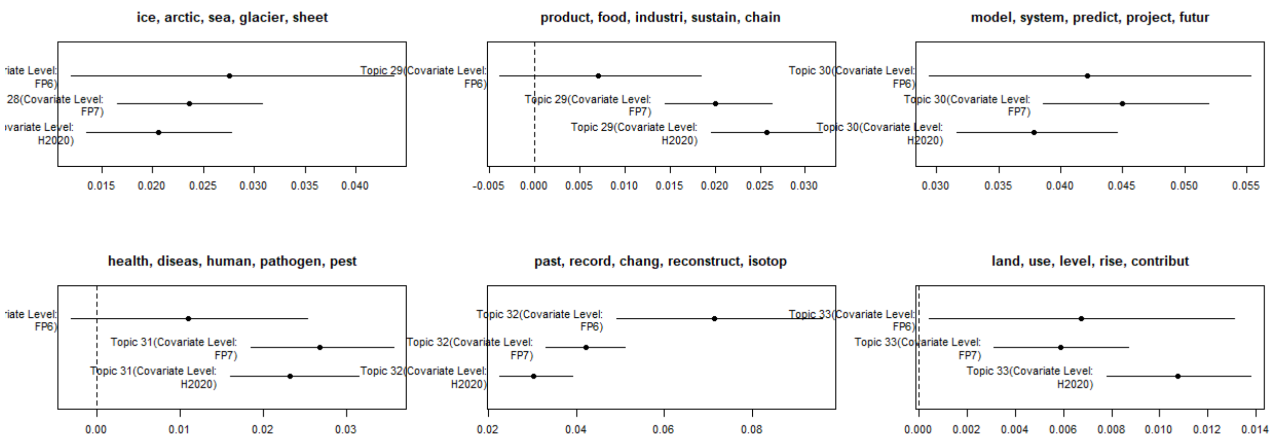
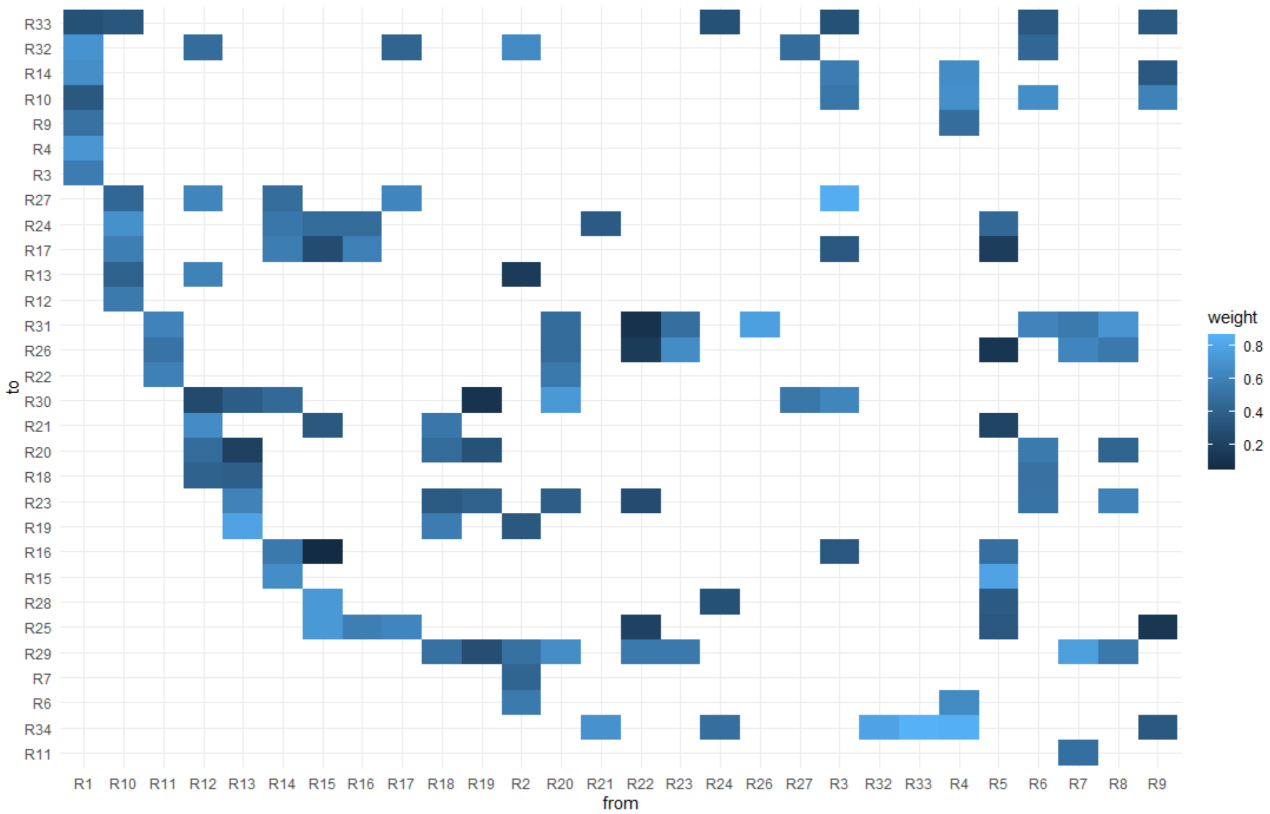


Figure 3.5S | Topics growth overtime – projects



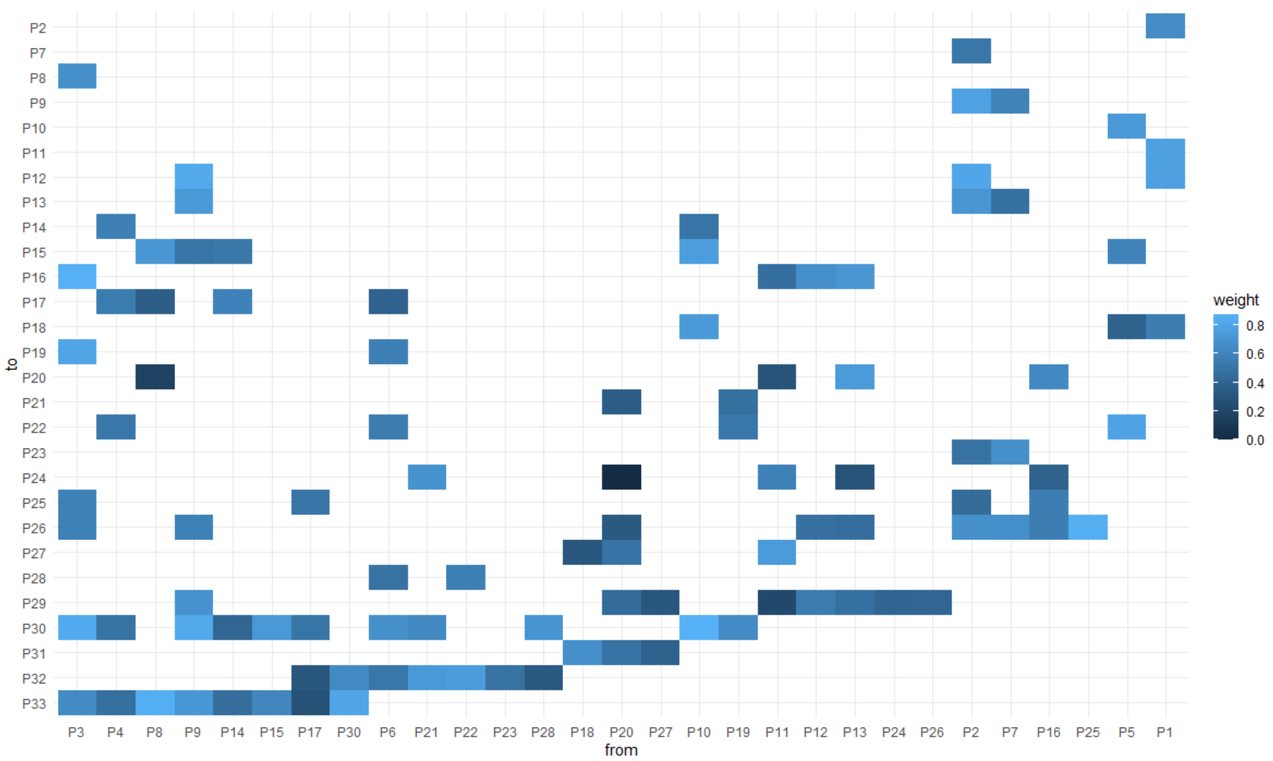


Figure 3.6S | Similarity between topics in the research and projects domains as computed by intra-domain cosine layers

Interview guidelines and pre-defined questions

Semi-structured interviews are the tools employed in this paper. Their use was justified by the desire to let the informant free to build her/his own narrative, while guided through the entire process. The interviewer clarified the characteristics and the goal of the Business Model Canvas. Interviews were built to collect information on the BMC's building blocks as by Hanshaw and Osterwalder (2015)[17]:

- Value Proposition
- Key Partners
- Key Activities
- Customer Relationships
- Key Resources
- Channels
- Cost Structure
- Revenue Streams

Furthermore, informants were asked about Barriers and Opportunities encountered throughout the design, development and marketing phases.

The following 17 questions were used as a roadmap of the interviews' process. The order in which they are hereby presented is not relevant, because the informant was let free to build her/his own storyline about the climate service.

Q0. Please, tell me more about ___. Throughout the chat, we are getting more specific on different aspects. In case you have any doubts about the terminology used, please do not hesitate to ask.

Q1. What is the value proposition of ____?

Q2. How is ___ using climate-related information? Is ____ a provider, a purveyor or both of climate information? [note that here we normally explain what we mean before asking and trying to contextualise]

Q3. What are the channels ___ is using to gather the required information that will serve as inputs for the service?

Q4. What are the main data sources?

Q5. Do you normally pay for input data? If yes, how much? (if they are not willing to share, we

[17] Hanshaw, N. and A. Osterwalder. 2015. *Why and how organizations around the world apply the business model canvas*. Strategyzer, Zurich, Switzerland.

normally ask them to give us an idea in percentage of the information acquisition costs)

Q6. (if a purveyor of can't define) What are the main providers of ___ ?

Q7. Who are the users/ customers __ is targeting?

Q8. (if they have not identified any specific user) How are you planning to identify your final user/customer?

Q9. How is ___ sharing the information?

Q10. Is ___ publicly available? Is __ selling the created information/model/product?

Q11. What was the main source of funding of ___?

Q12. Please describe the evolution overtime of this market according to your experience with ___? Is there a growing, steady or decreasing interest in these topics?

Q13. Which are the most common difficulties you face throughout the development of your service/product? Are there any cultural, social, psychological or economic barriers?

Q14. (in case of EU-funded projects) Do you have interactions with other projects? If yes, please describe how. Are they European only? If not, how do you interact with beyond-EU institutions/projects/activities?

Q15. (in case of private sector companies) In terms of competitors, please describe the evolution overtime and how you distinguish from the others? What is your value-added?

Q16. Are you aware of any other interested service/product/project currently implemented or under development?

List of realised interviews

- Allianz Global Investors
- Amundi Asset Management
- Avanzi Srl
- Business Integration Partners (BIP)
- Climate Adaptation Services (CAS)
- ClimRun
- Envirochange
- EticaSGR
- EU-Circle
- Euporias
- Ernst&Young Climate Change and Sustainability Services
- MOEEBIUS
- More-Connect
- Munich RE
- OASIS
- Thetis SpA
- Unipol
- Urban SIS
- Water-Ener-Cast (WEC)

- AirCloud
- AQCLI
- AQUA
- CLIME
- FloodMage
- GWh
- IRRICLIME
- PWA
- ROAT
- SCHT
- SEAP
- SHAT

- TCDF
- WRI

List of codes

Code Category	Codes
Channels	Blog Posts (News) Direct contact Maps Newsletter OpenSource Platform Reports Scientific Papers & Documents Social Networks Webpage Workshops_Conferences_Seminars
Cost structure	Data acquisition Data acquisition (variable) HR (Variable) HR Infrastructure&Maintenance Infrastructure&Maintenance (variable)
Customer Relationship	Co-creation development Co-finance Service provider Tailor-made service
Customer Segment	Civil Society (incl. NGOs) Policy Makers private Companies Public Entities Research Performing Organisations (RPOs)
Key Activities	Impact Assessment Modeling Policy Evaluation Prototype Development
Key Partners	Buyer-supplier relationship Competition

	Joint Venture Non-competitive Alliance
Key Resources	Financial resources Human resources Intellectual assets Physical assets
Revenue Stream	EU Funds Private funding Public funding (non-EU) Service fees Subscription-based
Value Proposition	Adaptation Advisory&Consultancy Compliance&Regulation Early-warning systems Economics&Finance Energy-efficiency Forecasts&Projections Fully functional service Information sharing Insurance products Mitigation Research Scenario Assessment Vulnerability&Risk Assessment

Opportunities	Growing awareness Increased data reliability Innovation
Bottlenecks&Barriers	Communication Data gaps Data quality Lack of awareness Lack of lont-term commitment

	Lack of market Lack of standards Technical difficulties

Descriptive statistics

Table 4.1 | Number of codings per code

Code	Freq	Code	Freq
Private Companies	47	Public funding (non-EU)	7
Co-creation dev.	36	Scientific Papers and Documents	7
Web-infrastructure	36	WaterForecasts	7
Innovation	35	buyer-supplier relation	6
PublicEntities	35	Early-warning systems	6
SeasonalForecasts	35	Financial resources	6
Non-competitive alliance	31	HR expenses	6
Tailor-made service	28	CivilSociety (incl.NGOs)	5
Joint Venture	26	Data acquisition (variable)	5
Energy-efficiency	23	Increased data reliability	5
Workshops_Conferences_Seminars	23	Private funding	5
PolicyMakers	22	Data Gaps	4
Direct contact	21	Data quality	4
Economics&Finance	21	Lack of standards	4
Forecasts&Projections	21	Competition	3
Modeling	21	Compliance&Regulation	3
EU Funds	20	Service provider	3
In-house expertise	20	Human resources	2
Fully Functional service	19	Infrastructure&Maintenance (variable)	2
Impact Assessment	19	Newsletter	2
Growing awareness	18	BlogPosts (News)	1
Lack of Awareness	18	HR (variable)	1
Research	18	SocialNetworks	1
Vulnerability&Risk Assessment	18		
Scenario Assessment	17		
Information Sharing	16		
Subscription-based	16		
Service Fees	15		
Adaptation	14		
Advisory&Consultancy	14		

Maps	14		
Prototype Development	14		
Communication	13		
Copernicus	13		
Infrastructure&Maintenance	13		
Technical difficulties	13		
OpenSource Platform	11		
Physical_assets	10		
Lack of long-term Committment	9		
Lack of market	9		
Data acquisition	8		
Insurance products	8		
Mitigation	8		
Reports	8		
RPOs	8		

Network Analysis

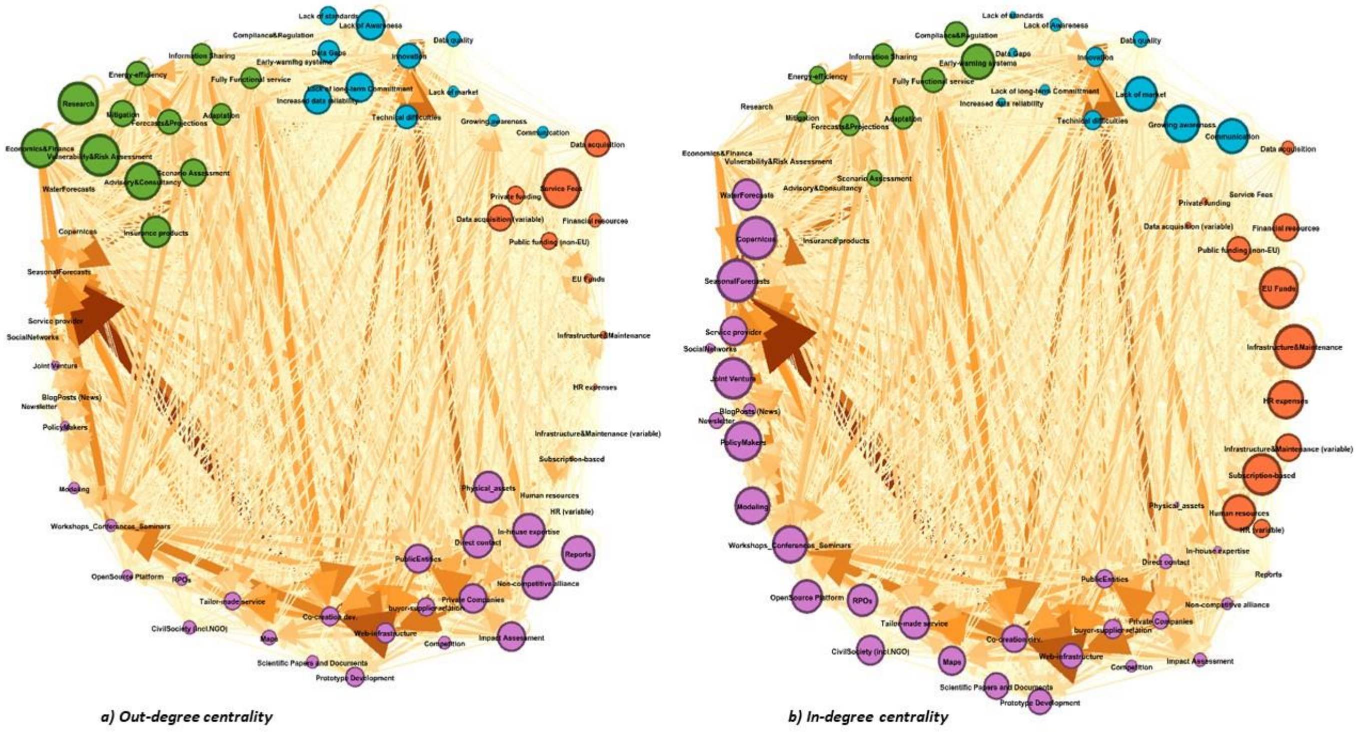


Figure 4.1S. Out-degree vs In-degree codes

The network of codes retrieved from the content analysis is represented using a circular mode, with clockwise node layout direction, avoiding label and node overlaps. Links are still weighted on the frequency of proximity within the same token of text. The size of the nodes is equivalent to the out-degree centrality measure (Figure 4.1Sa) and in-degree centrality (Figure 4.1Sb).

They are variants of the well-known degree centrality, defined as the number of links a given node has (Otte and Rousseau, 2002):

$$d(i) = \sum_{j} m_{ij}$$

where $m_{ij} = 1$ if there is a link between two nodes and $m_{ij} = 0$ otherwise.

Despite its wide employment, it is worth mentioning that Degree Centrality is a static and local measures, which only looks at a given node and its directly connected neighbors.

The out-degree centrality is expressed in mathematical notation as the sum of all the directed neighbors of node v and the node itself. In other words, it corresponds to the number of nodes directed outwards the node of interest:

$$c_{OD}(v) = d + (v)$$

where $d(v) = |N(v)|$ is the number of direct neighbors of v.

The in-degree centrality is intended as the opposite: it corresponds to all the nodes directed towards the node of interest:

$$c_{ID}(v) = d - (v)$$

PageRank is built on the consideration that a node acquires importance if it is already relevant or if it is linked to *(i)* important and *(ii)* parsimonious nodes. It is an eigenvector-based algorithm, used by Google engine to rank the pages in the World Wide Web. It requires directed networks. It is expressed in mathematical notation as:

$$C_{PR}(v) = (1 - d) + d\left[\frac{C_{PR}(t_1)}{C(t_1)} + \cdots + \frac{C_{PR}(t_n)}{C(t_n)}\right]$$

where v is the node of interest, $d \in [0,1]$ is the damping factor and $t_{1..n}$ are the nodes pointing towards v. As a result of the computation of PageRank, every node has a score assigned. This score is expressed in percentage format and can be interpreted as a fraction of the time "spent" on a given node. This percentage is measured over the total amount of available time following a revised random walk over all the vertices. PageRank does not determine the number required to a random walker, but rather a way to monitor the "diffusion" of a combination of random walks of various lengths (Brin and Page, 1998) using a positive and real value $\alpha \in [0,1)$. In other words, PageRank modifies existing centrality measures (e.g. Eigenvector centrality and Kats centrality) by assigning a fixed probability α of jumping from one random node (in our case a code) to another and a probability $(1 - \alpha)$ of ending up to a linked one. Therefore, the relevance of a given node v is the expected sum – discounted of a factor d – of the importance of all the previously existing nodes u.

Despite the existence of multiple centrality measures, PageRank is highly valuable in the context of this chapter because it has been historically conceived for a hypertextual environment (the World Wide Web). Furthermore, its mathematical structure is general and has already been applied in bibliometrics, information networks and social sciences (Gleich, 2014). PageRank is an alternative model of agent behavior that acts in a complex system (Brin and Page, 1998). Given we allowed informants to develop their own narrative during the interview, they can be considered as "random surfers" of the wide world of climate services provision, capable of "jumping" from one concept to another up to the point they start on another random topic.

Table 4.2 | Nodes ranking (by PageRank)

Label	PageRank	Label	PageRank
Infrastructure&Maintenance	54	Impact Assessment	17
SeasonalForecasts	53	BlogPosts (News)	17
Copernicus	53	Lack of Awareness	16
Joint Venture	51	Competition	16
EU Funds	51	Non-competitive alliance	15
Subscription-based	51	Lack of long-term Committment	13
PolicyMakers	49	Mitigation	13
HR expenses	48	SocialNetworks	13
Growing awareness	46	Data Gaps	12
Workshops_Conferences_Seminars	46	Increased data reliability	11
Modeling	46	Lack of standards	10
Human resources	45	Private funding	10
Early-warning systems	44	In-house expertise	9
Lack of market	43	Data acquisition (variable)	8
Communication	43	Physical_assets	7
OpenSource Platform	41	Insurance products	6
Tailor-made service	40	Reports	5
RPOs	40	Service Fees	4
WaterForecasts	39	Advisory&Consultancy	3
CivilSociety (incl.NGO)	38	Economics&Finance	2
Service provider	37	Vulnerability&Risk Assessment	1
Maps	36	Research	0
Infrastructure&Maintenance (variable)	35		
Co-creation dev.	34		
Financial resources	34		
Scientific Papers and Documents	33		
Prototype Development	32		
Fully Functional service	31		

Web-infrastructure	31		
Public funding (non-EU)	31		
Compliance&Regulation	31		
Adaptation	29		
Information Sharing	29		
Forecasts&Projections	26		
Innovation	24		
buyer-supplier relation	24		
Technical difficulties	24		
HR (variable)	24		
PublicEntities	23		
Private Companies	22		
Energy-efficiency	22		
Data quality	21		
Newsletter	21		
Scenario Assessment	20		
Direct contact	18		
Data acquisition	17		

Acknowledgements

There is a lovely Turkish saying - "To dig a well with a needle" – that well describes my feelings towards the passion for research and my choice to pursue a PhD degree. I feel extremely privileged, but mostly thankful because I could not do this alone and I was supported by so many.

A huge "thank you" to my family: to my sisters, Maddalena and Saveria, who inspire me with their lives, dreams, passions, and hard work. A special mention to my elder one, Maddalena, who will defend her PhD thesis the same days as I will. Sharing this journey with you has been a blessing. To my parents, who have supported the love for culture, knowledge, and study since my early childhood. To Umberto: thank you.

A warm thanks to my fellow PhD mates Charlie, Marta, Evans, Yinghao and Sara. I will never forget our fabulous, stylish, and globalized attitude towards the 1st year courses and life in general. You have inspired me with your research and your smiles. I hope to have you by my side for life. You have me by yours. To my Venetian PhD family, all around the world now and particularly to Paola, Francesco, Anna, Remo, Andrea and Silvia. To Venice, my lost paradise. I came back to you so many times and you are always there welcoming me again. In your *calli* I found life changing treasures. A big thanks to Lorenza and Gaia for having shared with me so many glorious memories. Thank you Marco for our path, "senza fretta, ma senza tregua". To my colleagues at CMCC who taught me something new everyday. Thank you to Stefano and Paolo from Gecosistema: you gave me so much I can hardly tell. To my Roman babes Flora and Giulia and to those I lived a beautiful year with. Those moments will stay with me forever. Thank you to my "never without" friend Luca: I love you so much.

Thank you Nadia for having welcomed me in your team at UCL, and thank you Sumit and Jamie for your inputs and comments. At the time of this submission, we have not met in person yet, but you are special colleagues to me. Thank you to my Leeds people (mostly Marta and Julia) for an unforgettable period abroad. Thank you to Prof. Carraro, his charisma and deep knowledge. This thesis is the outcome of many things. One above everyone saw them all: my mentor Jaro. I would not be here writing without you, our fights, our discussions, your inspiration and my stubbornness.

Time to celebrate. Per aspera ad astra!

DEPOSITO ELETTRONICO DELLA TESI DI DOTTORATO

DICHIARAZIONE SOSTITUTIVA DELL'ATTO DI NOTORIETA'

(ART. 47 D.P.R. 445 DEL 28/12/2000 E RELATIVE MODIFICHE)

Io sottoscritta Francesca Larosa
nata a La Spezia (prov. SP) il 29/08/1990
residente a La Spezia in Via Giacomo Doria n. 59

Matricola: 956338 Autore della tesi di dottorato dal titolo:
Complex networks in adaptation and mitigation to climate change
Dottorato di ricerca in Scienza e Gestione dei Cambiamenti Climatici, Ciclo 33
Anno di conseguimento del titolo: A.A. 2021/2022

DICHIARO

di essere a conoscenza:

1) del fatto che in caso di dichiarazioni mendaci, oltre alle sanzioni previste dal codice penale e dalle Leggi speciali per l'ipotesi di falsità in atti ed uso di atti falsi, decado fin dall'inizio e senza necessità di nessuna formalità dai benefici conseguenti al provvedimento emanato sulla base di tali dichiarazioni;

2) dell'obbligo per l'Università di provvedere, per via telematica, al deposito di legge delle tesi di dottorato presso le Biblioteche Nazionali Centrali di Roma e di Firenze al fine di assicurarne la conservazione e la consultabilità da parte di terzi;

3) che l'Università si riserva i diritti di riproduzione per scopi didattici, con citazione della fonte;

4) del fatto che il testo integrale della tesi di dottorato di cui alla presente dichiarazione viene archiviato e reso consultabile via Internet attraverso l'Archivio Istituzionale ad Accesso Aperto dell'Università Ca' Foscari, oltre che attraverso i cataloghi delle Biblioteche Nazionali Centrali di Roma e Firenze;

5) del fatto che, ai sensi e per gli effetti di cui al D.Lgs. n. 196/2003, i dati personali raccolti saranno trattati, anche con strumenti informatici, esclusivamente nell'ambito del procedimento per il quale la presentazione viene resa;

6) del fatto che la copia della tesi in formato elettronico depositato nell'Archivio Istituzionale ad Accesso Aperto è del tutto corrispondente alla tesi in formato cartaceo, controfirmata dal tutor, consegnata presso la segreteria didattica del dipartimento di riferimento del corso di dottorato ai fini del deposito presso l'Archivio di Ateneo, e che di conseguenza va esclusa qualsiasi responsabilità dell'Ateneo stesso per quanto riguarda eventuali errori, imprecisioni o omissioni nei contenuti della

tesi;

7) del fatto che la copia consegnata in formato cartaceo, controfirmata dal tutor, depositata nell'Archivio di Ateneo, è l'unica alla quale farà riferimento l'Università per rilasciare, a richiesta, la dichiarazione di conformità di eventuali copie;

09/12/2021 Francesca Larosa

NON AUTORIZZO

l'Università a riprodurre ai fini dell'immissione in rete e a comunicare al pubblico tramite servizio on line entro l'Archivio Istituzionale ad Accesso Aperto la tesi depositata per un periodo di 12 (dodici) mesi a partire dalla data di conseguimento del titolo di dottore di ricerca.

DICHIARO

1) che la tesi, in quanto caratterizzata da vincoli di segretezza, non dovrà essere consultabile on line da terzi per un periodo di 12 (dodici) mesi a partire dalla data di conseguimento del titolo di dottore di ricerca;

2) di essere a conoscenza del fatto che la versione elettronica della tesi dovrà altresì essere depositata a cura dell'Ateneo presso le Biblioteche Nazionali Centrali di Roma e Firenze dove sarà comunque consultabile su PC privi di periferiche; la tesi sarà inoltre consultabile in formato cartaceo presso l'Archivio Tesi di Ateneo;

3) di essere a conoscenza che allo scadere del dodicesimo mese a partire dalla data di conseguimento del titolo di dottore di ricerca la tesi sarà immessa in rete e comunicata al pubblico tramite servizio on line entro l'Archivio Istituzionale ad Accesso Aperto.

Specificare la motivazione:

X motivi di segretezza e/o di proprietà dei risultati e/o informazioni sensibili dell'Università Ca' Foscari di Venezia.

□ motivi di segretezza e/o di proprietà dei risultati e informazioni di enti esterni o aziende private che hanno partecipato alla realizzazione del lavoro di ricerca relativo alla tesi di dottorato.

□ dichiaro che la tesi di dottorato presenta elementi di innovazione per i quali è già stata attivata / si intende attivare la seguente procedura di tutela:

……………………………………………………………………………………………………;

X Altro (specificare):

Peer-review process for two papers currently forming part of the thesis

A tal fine:

- dichiaro di aver consegnato la copia integrale della tesi in formato elettronico tramite auto-archiviazione (upload) nel sito dell'Università; la tesi in formato elettronico sarà caricata automaticamente nell'Archivio Istituzionale ad Accesso Aperto dell'Università Ca' Foscari, dove rimarrà non accessibile fino allo scadere dell'embargo, e verrà consegnata mediante procedura telematica per il deposito legale presso la Biblioteca Nazionale Centrale di Firenze;
- consegno la copia integrale della tesi in formato cartaceo presso la segreteria didattica del dipartimento di riferimento del corso di dottorato ai fini del deposito presso l'Archivio di Ateneo.

Data 09/12/2021 Firma *Francesca Larosa*

La presente dichiarazione è sottoscritta dall'interessato in presenza del dipendente addetto, ovvero sottoscritta e inviata, unitamente a copia fotostatica non autenticata di un documento di identità del dichiarante, all'ufficio competente via fax, ovvero tramite un incaricato, oppure a mezzo posta.

Firma del dipendente addetto ………………………………………………………

Ai sensi dell'art. 13 del D.Lgs. n. 196/03 si informa che il titolare del trattamento dei dati forniti è l'Università Ca' Foscari - Venezia.
I dati sono acquisiti e trattati esclusivamente per l'espletamento delle finalità istituzionali d'Ateneo; l'eventuale rifiuto di fornire i propri dati personali potrebbe comportare il mancato espletamento degli adempimenti necessari e delle procedure amministrative di gestione delle carriere studenti. Sono comunque riconosciuti i diritti di cui all'art. 7 D. Lgs. n. 196/03.

ESTRATTO PER RIASSUNTO DELLA TESI DI DOTTORATO

Studente: Francesca Larosa

matricola: 956338

Dottorato: Scienza e Gestione dei Cambiamenti Climatici

Ciclo: 33

Titolo della tesi: Complex networks in adaptation and mitigation to climate change

Abstract (English):

The human-nature interaction is threatened by a changing climate. Innovative solutions are needed to limit the global warming, while promoting a sustainable future. Policy and action require new approaches that represent the complexity of and the interactions between multiple domains. The thesis shows how complex networks can achieve this goal. The thesis is structured in four chapters and presents applications in three domains: adaptation, mitigation and innovation. The first chapter maps the global landscape of climate services and shows how collaboration between different institutions stimulates the creation of information-based and technology-fueled innovations. The second chapter studies hydropower project financing, investors' behavior, and the optimal allocation of finance to support a just energy transition at global level. The third chapter assesses and measures the gap between research and action in Europe by combining network science and machine learning in an innovative and scalable framework. The fourth chapter explores how networks of words can inform about the optimal business models for climate services.

Abstract (Italian):

Soluzioni innovative per limitare il riscaldamento globale promuovendo al contempo uno sviluppo sostenibile e una equità sociale sono più che mai urgenti in presenza di cambiamento climatico. Per raggiungerle, politica e azione hanno bisogno del supporto di ricerche e metodi nuovi atti a rappresentare la complessità del reale. La tesi mostra come l'uso delle reti complesse possa rappresentare un valido aiuto. E' strutturata in quattro capitoli e descrive applicazioni in adattamento, mitigazione e innovazione per il cambiamento climatico. Il primo capitolo presenta una mappatura dei servizi climatici e mostra come la collaborazione crei sinergie per lo sviluppo di queste innovazioni. Il secondo capitolo studia la struttura finanziaria dei progetti idroelettrici e mostra come alcuni attori siano cruciali per favorire una transizione energetica equa. Il terzo capitolo misura la distanza tra ricerca e innovazione in Europa e scopre quali ambiti siano ancora inesplorati per raggiungere un continente ad emissioni zero. Nel quarto capitolo, le reti complesse rivelano quale siano le caratteristiche dei modelli di business dei servizi climatici.

Firma dello studente Francesca Larosa