Multiagent Climate Change Research

Blue Sky Ideas Track

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ABSTRACT

We call for attention to *climate change* research as a domain of application for *multiagent technologies*. The multiagent nature of climate change challenges and successful application of multiagent methods in decentralized power grid systems, market organization, and industrial engineering, could improve our ability to address decarbonization (climate change mitigation) and to deal with some unavoidable consequences of global warming (climate change adaptation). We review major challenges to which the community of multiagent systems can contribute, highlight open research problems and argue for the application of multiagent models and solution concepts in a variety of issues related to this global challenge.

KEYWORDS

Innovative Agents and Multiagent Applications, Agents for Climate Change, Emerging Applications of Agent-Based Systems, Multiagent Research for Global Challenges.

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1 INTRODUCTION

The overwhelming scientific consensus is that: *Earth's climate is warming and humans are the primary cause* [3, 20, 60]. Scientifically understood beyond any doubt, human-induced climate change from greenhouse gas emissions will modify the planet's physical systems in ways that will adversely impact our weather, how we grow food, the availability of fresh water and our ability to protect coastal regions. As a consequence, we urgently need to find ways to mitigate it and to adapt our life-style, our manufacturing processes, our economic systems and the operation of our cities. It is not a doomed situation but will be if we fail to deliver decarbonization globally within the coming decades. Following Pinker [66], we see the opportunity for applying available reasoning tools—in this case, from the Multiagent Systems (MAS) research—in the solutions needed and envisage a more enlightened future if we did so.

For such a socio-politically relevant issue, we suggest avoiding fast-thinking approaches/algorithms (in the sense of [37]) and instead apply rigorous and verifiable multiagent methods, engineering techniques, and coordination mechanisms, to address some of the problems in climate change. Challenges related to Climate Change (CC) mitigation and adaptation—by means of changing the decision processes—are multiagent in nature. In most CC challenges we deal with multiple competing actors/stakeholders, scarcity of resources, and coordination and cooperation problems. This motivates the use of techniques that are agent-based (not merely factor-based or event-based), which are able to capture social and behavioral aspects of (collective) decisions.[1]

While the sub-field of agent-based modeling/simulation[2] has contributed to this topic, it is an overlooked and under-represented application area in the rest of the MAS research community.[3] Mitigating climate change and adapting to it goes beyond *modeling*

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[1] We highlight that our focus is not on the ecological dimensions of the debate but on what the MAS community is capable of addressing.

[2] To clarify the setting for readers outside the agent research community, Agent Based Modeling (ABM) [30] has focus on gaining insight and explanation about the behavior of a (mostly real-life) phenomenon/system by means of computer simulation. As an umbrella field, multiagent systems research [34, 89] is concerned with questions on design, development, and coordination of systems that consist of various natural and/or artificial entities: including (among others) multiagent coordination models; multiagent engineering and problem-solving techniques; knowledge representation and reasoning frameworks; and strategic and game-theoretical solution concepts.

[3] According to ACM Digital Library (https://dlnext.acm.org/), from 6034 papers published in the proceedings of AAMAS from 1997 to 2019, we merely see 29 full papers, extended abstracts, and demonstrations (i.e., 0.48 %) that explicitly relate to *climate change* or *global warming*. This include the use of keywords that authors may use to refer to climate change and global warming in any part of the text. Our query was: *"climate change" OR "global warming" OR "climate action" OR "climate emergency" OR "environmental emergency" OR "environmental crisis" OR "ecological crisis" OR "climate challenge" OR "environmental challenge" OR "ecological challenge"*. These papers are from 20 authors and co-authors combined (0.24 % out of 8051 AAMAS authors).

scenarios and in addition requires *design*, *coordination*, and *governance* methods to foster social-ecological resilience and enable sustainable socio-technical transitions. As highlighted by Naomi Oreskes—in a reflection on the history of climate change research—"*climate change research overemphasized the importance of models and modeling*" [61].

We argue that, due to behavioral aspects, decision making with the aim to improve efficiencies (as a standard goal in optimization and operations research) is intrinsically different from, and hence inapt for, supporting decisions in view of disastrous events or existential risks. Moreover, we agree with [36, 62] that application of *purely* data-driven techniques are misleading.

In response, this work is the first attempt to articulate CC challenges to which the MAS community can contribute and is a starting point for establishing a research agenda for *Multiagent Climate Change (MACC)* research.

2 MACC RESEARCH

We focus on two main dimensions of the climate change research: Climate Change *Mitigation* and *Adaptation*.[4] For both dimensions, we briefly discuss current practices, elaborate on challenges and open research problems, and present a way forward by sketching multiagent methods that we see well-suited to investigating the problems.

2.1 Agents for Climate Change Mitigation

In principle, seeing the high possibility of disastrous environmental changes as result of humankind's interaction with the environment, a natural immediate response would be to *change how we act* to *mitigate* further damages. Examples include the way we consume resources (e.g., food types and the production of food and/or energy) and what we emit to the environment (e.g., as a result of transport, production processes, and burning of fossil fuels). In a nutshell, the focus of Climate Change (CC) mitigation research is on evaluating the effectiveness of potential forms of behavior change, their feasibility, and consequences [21, 25, 26, 92]. In this vein, we see three main challenges for which the community of multiagent systems has viable solution concepts and argue that although these problems are well-studied, the integration of multiagent techniques leads to capturing unaddressed dimensions.

Challenge 1 (Socio-Behavioral Pricing Schemes: Macroeconomic Coordination and Behavior Change). *The need for verifiable system-level (carbon) pricing schemes that are fair and stable in view of the behavioral and social aspects of climate change.*

[4]We see three dimensions to the Climate Change (CC) research: CC science, CC mitigation, and CC adaptation. In this work, we build on the results of CC science [39, 79] and assume that undesirable changes in the climate are a result of humankind's interventions and the use of environmentally-unfriendly technologies or decision making techniques. In response, we focus on what can be done—by highlighting the potentials of multiagent methods and technologies—to mitigate further damages and to adapt to unavoidable consequences. In principle, seeing CC scenarios as counterfactuals (as remote possibilities), the CC science is focused on improving our knowledge by relating what we know about actualities and what may happen (an epistemic problem). To compliment this, the focus of MACC research is on developing multiagent representation, reasoning, intervention, and decision support tools for analyzing and influencing eventualities based on our knowledge about actualities (a semantic problem). We deem that neither of the two suffice to address the climate change challenges while the combination (of CC science and MACC) is a permissible machination in our reasoning and solution-finding artillery.

Although carbon pricing is among one of the first policies aimed to mitigate emissions, investigating their effectiveness and ensuring their reliability remain open problems. One can argue that dismissing the social and behavioral aspects of climate change results in unrealistic assumptions (e.g., that firms are purely driven by short-term financial gains) and accordingly ineffective, or even counter-effective, pricing schemes. Reviewing recent trends and the state of the art on carbon pricing as a CC mitigation method [15, 41, 84], we see conceptual models (that are mostly unverifiable), factor-based techniques (that dismiss the agency of involved decision makers and the potential for emergence behaviors in their models), the rise of (model-free) data-driven techniques, and the absence of multiagent techniques and verifiable formal methods. We follow Pearl [62, 63] and argue that reasoning about interventions and their effectiveness needs sophisticated formal models. Moreover, if the main aim of pricing schemes is to nudge the behavior of macroeconomic entities (e.g., industrial firms) towards the environmentally friendly supply of resources or/and production technologies, the integration of social aspects is crucial. This is not simply to apply behavioral game theory but the integration of a range of social aspects (e.g., to capture trust and reputation). Introducing such aspects calls for tailoring multiagent social notions for the context of climate change (e.g., by building on formalizations in [16, 71]). This in turn enables developing systematically verifiable socio-behavioral (carbon) pricing tools.

Challenge 2 (Sustainable Incentivization: Microeconomic Coordination and Behavior Change). *The need for methods to analyse the reliability and effectiveness of incentive engineering techniques that aim to nudge the behavior of micro-level stakeholders towards a spectrum of sustainable behaviors.*

Focusing on micro-level entities and expecting that consumers opt for costly environmentally-friendly practices and products, is an unrealistic assumption. A natural response is to allocate incentives *in a reasonable and verifiable way* to nudge the collective choice and the change of behavior over time (e.g., in energy/food consumption and choice of transportation modes). This is related to macro-level pricing schemes, and raises distinct problems. For instance, currently we have products that are produced in a sustainable manner (so we can say the macro-level coordination was successful) but they may require subsidies to become attractive to consumers. While we see the application of methods from operations research and economic theory to this problem [45, 75, 88, 96], we suggest a line of scientific research to capture the agency of stakeholders and their propensity to follow social norms. To this end, one main avenue would be to employ norm-aware coordination mechanisms [8, 13] for incentive engineering. Such methods are effective in other contexts (e.g., in business administration and natural resource management) and are expressive-enough for specifying desirable properties in the context of climate change.

Challenge 3 (Climate Liability Determination/Sharing Methods). *The need for automatized methods for liability evaluation and responsibility sharing in the context of climate change litigation.*

In various judiciary cases related to climate change and environmental damage [64, 76], we observe *responsibility gaps* and variations of the *problem of many hands*.[5] If you take the example of recent (energy corporation) court cases where responsibility is shared among oil and natural resources corporations, individuals and governing entities who are responsible for the occurrence of undesirable outcomes, determining who is to blame—and more importantly *to what extent*—requires rigorous methods. Such methods are expected to capture strategic, epistemic and temporal subtleties of the problem. We argue that the complexity of such problems calls for automated methods to support judiciary decisions. Building on [18, 87], we see the potential for application and tailoring of multiagent responsibility reasoning techniques. Agent-oriented causal responsibility ascription [18], moral notions of responsibility [10], and strategic responsibility reasoning [93] could formally address challenges in responsibility reasoning and have the potential to capture various dimensions of climate change litigation cases.

2.2 Agents for Climate Change Adaptation

For decades, much climate change research was focused on mitigation [92]. However, to deal with now unavoidable consequences, adaptation strategies and decision support tools are necessary. Thus, in this section, we look at CC adaptation [1, 2, 54] and highlight open research avenues and challenges. These are not necessary capturing *all* the challenges in the field of CC adaptation but are mainly focused on the class of challenges to which the community of AAMAS can contribute by providing solution concepts.

Challenge 4 (Adaptive Financial Measures and Insurance Mechanisms). *The need for dynamic economic systems and multiagent organizational models to enable reorganization in response to radical changes.*

Observing the occurrence of radical changes in the climate (and seeing predictions that high-impact events will increase in frequency and magnitude), it is questionable whether *"all loss and damage from climate change can be covered"* by insurance [44, 48]. Recent studies show that (potential) costs can not be fully covered by insurance companies, and that climate change may result in situations where insurance companies avoid covering the most vulnerable areas (e.g., in the case of flood insurance, river-bank residential/industrial buildings). To avoid such outcomes, reorganization of final measures and insurance mechanisms is necessary. For such a purpose, the body of work on *multiagent organizational frameworks*, principles for *self-organizing institutions*, and methods for *adaptive re-organization* [4, 57, 67, 80] have promising potential. In particular, they can provide computational organizational models in the context of CC insurance and a formal basis for evaluating and improving the reliability and adaptability of financial and insurance mechanisms [82, 83].

Challenge 5 (Transitional Business Models for Circular Economy). *The need for business models to foster the transition from a linear towards a circular economy.*

In contrast to traditional linear-economic models (to take resources, produce and discharge the waste), the concept of the circular economy is focused on reusable resources among industrial firms [17, 40]. Due to the non-commodity nature of such resources (e.g., waste energy and material), price-based techniques are effective neither for initiation nor for operation of such relations. (A similar situation on inapplicability of price-based techniques can be observed in kidney-matching, for example [29, 72].) Thus, realizing such a form of collaboration requires tailored operations-oriented methods for identifying potential matches, evaluating them to generate mutually beneficial instances, implementing cost-sharing schemes in bilateral contracts and decentralized governance of the established relations.[6] We observe, in real-life practices (e.g., see successful cases in the SHAREBOX project [77]), that if firms apply systematically verified decision support tools for making decisions in various phases of industrial symbiosis, the practice is not only a sustainable choice but also a profitable one. In other words, they can evaluate collaborative potentials in a systematic manner. Therefore, we see the potential to build on the line of research on *multiagent industrial symbiosis systems* [94, 95] to support the decision processes for implementing the transition towards a circular economy.

Challenge 6 (Climate Change Policy-Effectiveness Analysis and Conflict-Free Rules). *The need for methods to analyze the effectiveness of policies and develop conflict-free rules.*

To ensure adaptability with CC—in urban, rural, and industrial areas—Agent-Based Modeling (ABM) and simulation techniques are among the most well-established techniques in the CC literature [33]. Despite early attempts in which agents' decision rules were merely based on economic theories (and sometimes in conflict with the reality of CC scenarios), there is an ongoing trend to inform ABM rules using participatory techniques such as fuzzy cognitive maps and serious games [50, 51, 78]. However, as [6] discusses, this may lead to modeling dilemmas for which novel multi-modal knowledge aggregation and representation tools are required. In particular, to analyze the effectiveness of CC policies, we lack methods able to represent various forms of qualitative and quantitative knowledge as well as reasoning tools to highlight the class of conflict-free ABM rules. For the former, we see that multiagent logic-based knowledge representation models [7, 91] are appropriate and expressive-enough to be tailored for integrating qualitative and quantitative forms of knowledge in CC scenarios. And to address conflict-freeness, integration of methods from multiagent argumentation theory is viable [24, 43, 69].

3 CONCLUDING REMARKS

We introduce MACC research as an interdisciplinary field to foster the application of various multiagent methodologies for climate change mitigation and adaptation (see Figure 1). We would like to highlight differences in the so called *"methodology readiness"* of MAS techniques for addressing CC challenges, e.g., to address Challenge 3–6, MAS techniques have a higher readiness/maturity to be applied in the context of CC (in comparison to those in Challenge 1 and 2). This motivates more work, but not in a serial way (i.e., to build theories, wait for their maturity and then apply them to

[5]This problem refers to cases where a group is responsible for a state of affairs but it is not straightforward to determine the extent of responsibility of each member [22, 47].

[6]Reducing the material and energy footprint of firms is directly linked to sustainability gains and fits their business model with respect to Corporate Social Responsibility (CSR) goals [35]. But the question is: will it result in a sufficient cost reduction to compensate the opportunity costs that firms may face to focus on industrial symbiosis?

Figure 1: Multiagent Climate Change Research (Methodological Subdisciplines and Related Work).

CC). We argue that contextualization should be embedded from the beginning for both micro and macro level coordination techniques (in Challenges 1 and 2).

The next steps are to develop a roadmap for MACC research where we clarify its relations with neighbouring disciplines—e.g., with environmental economics [81, 85], AI for sustainable development [12, 27], and work relating to societal well-being and potential existential risks [9, 31, 38]—and focus on concrete CC problems in which multiagent technologies are applicable.

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REFERENCES

[1] W Neil Adger, Nigel W Arnell, and Emma L Tompkins. 2005. Successful adaptation to climate change across scales. *Global environmental change* 15, 2 (2005), 77–86.

[2] W Neil Adger, Suraje Dessai, Marisa Goulden, Mike Hulme, Irene Lorenzoni, Donald R Nelson, Lars Otto Naess, Johanna Wolf, and Anita Wreford. 2009. Are there social limits to adaptation to climate change? *Climatic change* 93, 3-4 (2009), 335–354.

[3] NASA: The National Aeronautics and Space Administration. 2019. Scientific Consensus: Earth's Climate is Warming. https://climate.nasa.gov/scientific-consensus/. (2019). Accessed: 2020-02-10.

[4] Huib Aldewereld, Frank Dignum, Virginia Dignum, and Loris Penserini. 2009. A Formal Specification for Organizational Adaptation. In *Agent-Oriented Software Engineering X - 10th International Workshop, AOSE 2009, Budapest, Hungary, May 11-12, 2009, Revised Selected Papers*. Springer, Berlin, Heidelberg, 18–31. https://doi.org/10.1007/978-3-642-19208-1_2

[5] Natasha Alechina and Brian Logan. 2018. Resource Logics with a Diminishing Resource. In *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems (AAMAS '18)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 1847–1849.

[6] Andrew E. F. Allison, Mark E. Dickson, Karen T. Fisher, and Simon F. Thrush. 2018. Dilemmas of modelling and decision-making in environmental research. *Environmental Modelling and Software* 99 (2018), 147–155. https://doi.org/10.1016/j.envsoft.2017.09.015

[7] Jamal Bentahar, Bernard Moulin, and Micheline Bélanger. 2010. A taxonomy of argumentation models used for knowledge representation. *Artificial Intelligence Review* 33, 3 (2010), 211–259.

[8] Guido Boella and Leendert WN van der Torre. 2004. Regulative and constitutive norms in normative multiagent systems. *KR* 4 (2004), 255–265.

[9] Nick Bostrom. 2009. The future of humanity. In *New waves in philosophy of technology*. Palgrave Macmillan, London, United Kingdom, 186–215.

[10] Matthew Braham and Martin Van Hees. 2012. An anatomy of moral responsibility. *Mind* 121, 483 (2012), 601–634.

[11] Felix Brandt, Vincent Conitzer, Ulle Endriss, Jérôme Lang, and Ariel D Procaccia. 2016. *Handbook of computational social choice*. Cambridge University Press, Cambridge, United Kingdom.

[12] Tung X Bui. 2002. Decision support systems for sustainable development. In *Decision Support Systems for Sustainable Development*. Springer, Boston, MA, USA, 1–10.

[13] Nils Bulling and Mehdi Dastani. 2016. Norm-based mechanism design. *Artificial Intelligence* 239 (2016), 97–142.

[14] Martin Caminada and Chiaki Sakama. 2015. On the issue of argumentation and informedness. In *JSAI International Symposium on Artificial Intelligence*. Springer, Switzerland, Cahm, 317–330.

[15] Emanuele Campiglio. 2016. Beyond carbon pricing: The role of banking and monetary policy in financing the transition to a low-carbon economy. *Ecological Economics* 121 (2016), 220–230.

[16] Christiano Castelfranchi and Rino Falcone. 2010. *Trust theory: A socio-cognitive and computational model*. Vol. 18. John Wiley & Sons, Chichester, United Kingdom.

[17] Marian R. Chertow. 2007. "Uncovering" Industrial Symbiosis. *Journal of Industrial Ecology* 11, 1 (2007), 11–30. https://doi.org/10.1162/jiec.2007.1110

[18] Hana Chockler and Joseph Y Halpern. 2004. Responsibility and blame: A structural-model approach. *Journal of Artificial Intelligence Research* 22 (2004), 93–115.

[19] Rosaria Conte, Cristiano Castelfranchi, and Frank Dignum. 1998. Autonomous norm acceptance. In *International Workshop on Agent Theories, Architectures, and Languages*. Springer, Berlin, Heidelberg, 99–112.

[20] John Cook, Naomi Oreskes, Peter T Doran, William RL Anderegg, Bart Verheggen, Ed W Maibach, J Stuart Carlton, Stephan Lewandowsky, Andrew G Skuce, Sarah A Green, et al. 2016. Consensus on consensus: a synthesis of consensus estimates on human-caused global warming. *Environmental Research Letters* 11, 4 (2016), 048002.

[21] Felix Creutzig, Nijavalli H Ravindranath, Göran Berndes, Simon Bolwig, Ryan Bright, Francesco Cherubini, Helena Chum, Esteve Corbera, Mark Delucchi, Andre Faaij, et al. 2015. Bioenergy and climate change mitigation: an assessment. *Gcb Bioenergy* 7, 5 (2015), 916–944.

[22] Etienne de Villiers. 2002. Who will bear moral responsibility? *Communicatio* 28 (2002), 16–21.

[23] Francien Dechesne, Amineh Ghorbani, and Neil Yorke-Smith. 2015. Introduction to the special issue on agent-based modelling for policy engineering. *AI & SOCIETY* 30, 3 (2015), 311–313.

[24] Phan Minh Dung. 1995. On the acceptability of arguments and its fundamental role in nonmonotonic reasoning, logic programming and n-person games. *Artificial intelligence* 77, 2 (1995), 321–357.

[25] Ottmar Edenhofer. 2015. *Climate change 2014: mitigation of climate change*. Vol. 3. Cambridge University Press, Cambridge, United Kingdom.

[26] Ottmar Edenhofer, Ramon Pichs-Madruga, Youba Sokona, and Kristin Seyboth (Eds.). 2011. *IPCC special report on renewable energy sources and climate change mitigation*. Cambridge University Press, Cambridge, United Kingdom.

[27] Omar F. El-Gayar and Brian D. Fritz. 2006. Environmental Management Information Systems (EMIS) for Sustainable Development: A Conceptual Overview. *CAIS* 17 (2006), 34.

[28] L. Fraccascia, V. Yazdanpanah, G. van Capelleveen, and D. M. Yazan. 2019. A Framework for Industrial Symbiosis Systems for Agent-Based Simulation. In *2019 IEEE 21st Conference on Business Informatics (CBI)*, Vol. 01. IEEE, New Jersey, USA, 419–428. https://doi.org/10.1109/CBI.2019.00055

[29] Rachel Freedman, Jana Schaich Borg, Walter Sinnott-Armstrong, John P. Dickerson, and Vincent Conitzer. 2018. Adapting a Kidney Exchange Algorithm to Align With Human Values. In *Proceedings of AAAI-2018*. AAAI Publications, Palo Alto, CA, USA, 1636–1643.

[30] Nigel Gilbert. 2008. *Agent-based models*. Sage Publications, Incorporated, London, United Kingdom.

[31] Henner Gimpel. 2015. Interview with Thomas W. Malone on "Collective Intelligence, Climate Change, and the Future of Work". *Business & Information Systems Engineering* 57, 4 (2015), 275–278.

[32] Francisco Grimaldo, Miguel Lozano, Fernando Barber, and Alejandro Guerra-Hernández. 2012. Towards a model for urban mobility social simulation. *Progress in Artificial Intelligence* 1, 2 (2012), 149–156.

[33] Atesmachew Hailegiorgis, Andrew Crooks, and Claudio Cioffi-Revilla. 2018. An Agent-Based Model of Rural Households' Adaptation to Climate Change. *Journal of Artificial Societies and Social Simulation* 21, 4 (2018), 4. https://doi.org/10.18564/jasss.3812

[34] Nicholas R Jennings, Katia Sycara, and Michael Wooldridge. 1998. A roadmap of agent research and development. *Autonomous agents and multi-agent systems* 1, 1 (1998), 7–38.

[35] Thomas M Jones. 1980. Corporate social responsibility revisited, redefined. *California management review* 22, 3 (1980), 59–67.

[36] Lynn Helena Kaack. 2019. *Challenges and Prospects for Data-Driven Climate Change Mitigation*. Ph.D. Dissertation. Carnegie Mellon University.

[37] Daniel Kahneman. 2011. *Thinking, fast and slow*. Macmillan, London, United Kingdom.

[38] Peter Kareiva and Valerie Carranza. 2018. Existential risk due to ecosystem collapse: Nature strikes back. *Futures* 102 (2018), 39–50.

[39] David A King. 2004. Climate change science: adapt, mitigate, or ignore? (2004).

[40] Julian Kirchherr, Denise Reike, and Marko Hekkert. 2017. Conceptualizing the circular economy: An analysis of 114 definitions. *Resources, Conservation and Recycling* 127 (2017), 221–232.

[41] Alexandre Kossoy. 2015. *State and trends of carbon pricing 2015*. World Bank Publications, Washington DC, USA.

[42] Jun-young Kwak, Pradeep Varakantham, Rajiv Maheswaran, Milind Tambe, Farrokh Jazizadeh, Geoffrey Kavulya, Laura Klein, Burcin Becerik-Gerber, Timothy Hayes, and Wendy Wood. 2012. SAVES: A Sustainable Multiagent Application to Conserve Building Energy Considering Occupants. In *Proceedings of the 11th International Conference on Autonomous Agents and Multiagent Systems - Volume 1 (AAMAS '12)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 21–28.

[43] Hengfei Li, Nir Oren, and Timothy J. Norman. 2011. Probabilistic Argumentation Frameworks. In *Theorie and Applications of Formal Argumentation - First International Workshop, TAFA 2011. Barcelona, Spain, July 16-17, 2011, Revised Selected Papers*. Springer, Berlin, Heidelberg, 1–16. https://doi.org/10.1007/978-3-642-29184-5_1

[44] JoAnne Linnerooth-Bayer, Swenja Surminski, Laurens M Bouwer, Ilan Noy, and Reinhard Mechler. 2019. Insurance as a Response to Loss and Damage? In *Loss and Damage from Climate Change*. Springer, Switzerland, Cham, 483–512.

[45] Todd Litman and David Burwell. 2006. Issues in sustainable transportation. *International Journal of Global Environmental Issues* 6, 4 (2006), 331–347.

[46] Menelaos Makriyiannis, Tudor Lung, Robert Craven, Francesca Toni, and Jack Kelly. 2016. Smarter electricity and argumentation theory. In *Combinations of Intelligent Methods and Applications*. Springer, Switzerland, Cahm, 79–95.

[47] Rosja Mastop. 2010. Characterising responsibility in organisational structures: The problem of many hands. In *International Conference on Deontic Logic in Computer Science*. Springer, Berlin, Heidelberg, 274–287.

[48] Reinhard Mechler, Elisa Calliari, Laurens M Bouwer, Thomas Schinko, Swenja Surminski, JoAnne Linnerooth-Bayer, Jeroen Aerts, Wouter Botzen, Emily Boyd, Natalie Delia Deckard, et al. 2019. Science for loss and damage. Findings and propositions. In *Loss and Damage from Climate Change*. Springer, Switzerland, Cham, 3–37.

[49] Sara Mehryar. 2019. *Participatory Policy Analysis in Climate Change Adaptation: From individual perceptions to collective behaviour*. Number 343 in ITC Dissertation. University of Twente, Faculty of Geo-Information Science and Earth Observation (ITC), Enschede, The Netherlands. https://doi.org/10.3990/1.9789036547260

[50] Sara Mehryar, Richard Sliuzas, Nina Schwarz, Ali Sharifi, and Martin van Maarseveen. 2019. From individual Fuzzy Cognitive Maps to Agent Based Models: Modeling multi-factorial and multi-stakeholder decision-making for water scarcity. *Journal of environmental management* 250 (2019), 109482.

[51] Sara Mehryar, Richard Sliuzas, Ali Sharifi, Diana Reckien, and Martin van Maarseveen. 2017. A structured participatory method to support policy option analysis in a social-ecological system. *Journal of environmental management* 197 (2017), 360–372.

[52] Rijk Mercuur, Frank Dignum, and Yoshihisa Kashima. 2017. Changing habits using contextualized decision making. In *Advances in social simulation 2015*. Springer, Switzerland, Cham, 267–272.

[53] Georgios Methenitis, Michael Kaisers, and Han La Poutré. 2019. Forecast-Based Mechanisms for Demand Response. In *Proceedings of the 18th International Conference on Autonomous Agents and MultiAgent Systems (AAMAS '19)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 1600–1608.

[54] Susanne C Moser and Julia A Ekstrom. 2010. A framework to diagnose barriers to climate change adaptation. *Proceedings of the national academy of sciences* 107, 51 (2010), 22026–22031.

[55] Mackenzie B Murphy, Georgia Mavrommati, Varun Rao Mallampalli, Richard B Howarth, and Mark E Borsuk. 2017. Comparing group deliberation to other forms of preference aggregation in valuing ecosystem services. *Ecology and Society* 22, 4 (2017), 17.

[56] Kathleen Newland. 2011. *Climate change and migration dynamics*. Migration Policy Institute, Washington DC, USA.

[57] Pablo Noriega, Amit K. Chopra, Nicoletta Fornara, Henrique Lopes Cardoso, and Munindar P. Singh. 2013. Regulated MAS: Social Perspective. In *Normative Multi-Agent Systems*, Giulia Andrighetto, Guido Governatori, Pablo Noriega, and Leendert W. N. van der Torre (Eds.). Dagstuhl Follow-Ups, Vol. 4. Schloss Dagstuhl–Leibniz-Zentrum fuer Informatik, Dagstuhl, Germany, 93–133. https://doi.org/10.4230/DFU.Vol4.12111.93

[58] Philipp Obreiter, Birgitta König-Ries, and Georgios Papadopoulos. 2004. Engineering incentive schemes for ad hoc networks. In *International Conference on Extending Database Technology*. Springer, Berlin, Heidelberg, 395–404.

[59] Gregory M. P. O'Hare, Michael J. O'Grady, Richard Tynan, Conor Muldoon, Harry R. Kolar, Antonio G. Ruzzelli, Dermot Diamond, and E. Sweeney. 2007. Embedding intelligent decision making within complex dynamic environments. *Artif. Intell. Rev.* 27, 2-3 (2007), 189–201. https://doi.org/10.1007/s10462-008-9089-y

[60] Naomi Oreskes. 2004. The scientific consensus on climate change. *Science* 306, 5702 (2004), 1686–1686.

[61] Naomi Oreskes. 2019. Personal Communication at a book presentation by Professor Naomi Oreskes. http://www.lse.ac.uk/GranthamInstitute/event/why-trust-science-a-talk-by-professor-naomi-oreskes/. (2019). Question and Answer Section of the Book Presentation: Why trust science? A talk by Professor Naomi Oreskes, London School of Economics, London, UK, 19-09-2019.

[62] Judea Pearl. 2018. Theoretical Impediments to Machine Learning With Seven Sparks from the Causal Revolution. In *Proceedings of the Eleventh ACM International Conference on Web Search and Data Mining (WSDM '18)*. Association for Computing Machinery, New York, NY, USA, 3. https://doi.org/10.1145/3159652.3176182

[63] Judea Pearl and Dana Mackenzie. 2018. *The book of why: the new science of cause and effect*. Basic Books, New York, USA.

[64] Jacqueline Peel and Hari M Osofsky. 2015. *Climate Change Litigation*. Cambridge University Press, Cambridge, United Kingdom.

[65] Klara Pigmans, Huib Aldewereld, Virginia Dignum, and Neelke Doorn. 2019. The role of value deliberation to improve stakeholder participation in issues of water governance. *Water Resources Management* 3 (2019), 4067–4085.

[66] Steven Pinker. 2018. *Enlightenment now: The case for reason, science, humanism, and progress*. Penguin, United Kingdom.

[67] Jeremy Pitt, Julia Schaumeier, and Alexander Artikis. 2012. Axiomatization of Socio-Economic Principles for Self-Organizing Institutions: Concepts, Experiments and Challenges. *ACM Trans. Auton. Adapt. Syst.* 7, 4, Article Article 39 (Dec. 2012), 39 pages. https://doi.org/10.1145/2382570.2382575

[68] J Gareth Polhill, Jiaqi Ge, Matthew P Hare, Keith B Matthews, Alessandro Gimona, Douglas Salt, and Jagadeesh Yeluripati. 2019. Crossing the chasm: a 'tube-map'for agent-based social simulation of policy scenarios in spatially-distributed systems. *GeoInformatica* 23, 2 (2019), 169–199.

[69] Henry Prakken. 2010. An abstract framework for argumentation with structured arguments. *Argument and Computation* 1, 2 (2010), 93–124.

[70] Sarvapali Ramchurn, Perukrishnen Vytelingum, Alex Rogers, and Nicholas R Jennings. 2012. Putting the" smarts" into the smart grid: A grand challenge for artificial intelligence. *Commun. ACM* 55, 4 (2012), 86–97.

[71] Sarvapali D Ramchurn, Dong Huynh, and Nicholas R Jennings. 2004. Trust in multi-agent systems. *The Knowledge Engineering Review* 19, 1 (2004), 1–25.

[72] Alvin E. Roth, Tayfun Sönmez, and M. Utku Ünver. 2005. Pairwise kidney exchange. *Journal of Economic theory* 125, 2 (2005), 151–188.

[73] Bastin Tony Roy Savarimuthu, Rexy Arulanandam, and Maryam Purvis. 2011. Aspects of active norm learning and the effect of lying on norm emergence in agent societies. In *International Conference on Principles and Practice of Multi-Agent Systems*. Springer, Berlin, Heidelberg, 36–50.

[74] Norman Schofield. 2016. Climate Change, Catastrophic Risks and Social Choice Theory. In *The Economics of the Global Environment*. Springer, Switzerland, Cham, 389–421.

[75] Tomás Serebrisky, Andrés Gómez-Lobo, Nicolás Estupiñán, and Ramón Muñoz-Raskin. 2009. Affordability and subsidies in public urban transport: what do we mean, what can be done? *Transport reviews* 29, 6 (2009), 715–739.

[76] Joana Setzer and Lisa C Vanhala. 2019. Climate change litigation: A review of research on courts and litigants in climate governance. *Wiley Interdisciplinary Reviews: Climate Change* 10, 3 (2019), e580.

[77] SHAREBOX. 2019. Secure Sharing. http://sharebox-project.eu/. (2019). Accessed: 2020-02-10.

[78] Linda Shenk, Caroline Krejci, and Ulrike Passe. 2019. Agents of change—together: Using agent-based models to inspire social capital building for resilient communities. *Community Development* 50, 2 (2019), 256–272. https://doi.org/10.1080/15575330.2019.1574849 arXiv:https://doi.org/10.1080/15575330.2019.1574849

[79] Martin J Siegert. 2001. *Ice sheets and late Quaternary environmental change*. John Wiley Hoboken, New Jersey, USA.

[80] Carles Sierra, John Thangarajah, Lin Padgham, and Michael Winikoff. 2006. Designing Institutional Multi-Agent Systems. In *Agent-Oriented Software Engineering VII, 7th International Workshop, AOSE 2006, Hakodate, Japan, May 8, 2006, Revised and Invited Papers*. Springer, Berlin, Heidelberg, 84–103. https://doi.org/10.1007/978-3-540-70945-9_6

[81] Nicholas Stern. 2008. The economics of climate change. *American Economic Review* 98, 2 (2008), 1–37.

[82] Swenja Surminski, Laurens M Bouwer, and Joanne Linnerooth-Bayer. 2016. How insurance can support climate resilience. *Nature Climate Change* 6, 4 (2016), 333–334.

[83] Swenja Surminski and Delioma Oramas-Dorta. 2014. Flood insurance schemes and climate adaptation in developing countries. *International Journal of Disaster Risk Reduction* 7 (2014), 154–164.

[84] Tom H Tietenberg. 2013. Reflections—carbon pricing in practice. *Review of Environmental Economics and Policy* 7, 2 (2013), 313–329.

[85] Thomas H Tietenberg and Lynne Lewis. 2016. *Environmental and natural resource economics*. Routledge, New York, USA.

[86] Ibo Van de Poel. 2011. The relation between forward-looking and backward-looking responsibility. In *Moral responsibility*. Springer, Dordrecht, The Netherlands, 37–52.

[87] Ibo Van de Poel, Jessica Nihlén Fahlquist, Neelke Doorn, Sjoerd Zwart, and Lamber Royakkers. 2012. The problem of many hands: Climate change as an example. *Science and engineering ethics* 18, 1 (2012), 49–67.

[88] Ping Wang, Qian Liu, and Yu Qi. 2014. Factors influencing sustainable consumption behaviors: a survey of the rural residents in China. *Journal of Cleaner Production* 63 (2014), 152–165.

[89] Michael Wooldridge. 2009. *An introduction to multiagent systems*. John Wiley & Sons, Chichester, United Kingdom.

[90] Michael Wooldridge, Ulle Endriss, Sarit Kraus, and Jérôme Lang. 2013. Incentive engineering for Boolean games. *Artificial Intelligence* 195 (2013), 418–439.

[91] Michael Wooldridge and Alessio Lomuscio. 1999. Reasoning about visibility, perception, and knowledge. In *International Workshop on Agent Theories, Architectures, and Languages*. Springer, Berlin, Heidelberg, 1–12.

[92] Ernst Worrell, Lenny Bernstein, Joyashree Roy, Lynn Price, and Jochen Harnisch. 2009. Industrial energy efficiency and climate change mitigation. *Energy efficiency* 2, 2 (2009), 109.

[93] Vahid Yazdanpanah, Mehdi Dastani, Wojciech Jamroga, Natasha Alechina, and Brian Logan. 2019. Strategic Responsibility Under Imperfect Information. In *Proceedings of the 18th International Conference on Autonomous Agents and Multi-Agent Systems (AAMAS '19)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 592–600.

[94] Vahid Yazdanpanah, Devrim Murat Yazan, and Henk Zijm. 2018. Industrial Symbiotic Networks as Coordinated Games. In *Proceedings of the 17th International Conference on Autonomous Agents and MultiAgent Systems (AAMAS '18)*. International Foundation for Autonomous Agents and Multiagent Systems, Richland, SC, 2145–2147.

[95] Vahid Yazdanpanah, Devrim Murat Yazan, and W Henk M Zijm. 2019. FISOF: A formal industrial symbiosis opportunity filtering method. *Engineering applications of artificial intelligence* 81 (2019), 247–259.

[96] William Young, Kumju Hwang, Seonaidh McDonald, and Caroline J Oates. 2010. Sustainable consumption: green consumer behaviour when purchasing products. *Sustainable development* 18, 1 (2010), 20–31.