DOI: 10.1111/jiec.13006

JOURNAL OF INDUSTRIAL ECOLOGY WILEY

EDITORIAL

Industrial ecology in support of climate change adaptation

"This special issue was developed to advance thinking on how industrial ecology can support climate adaptation. The articles show ways in which established industrial ecology approaches can shift from the mitigation to adaptation realms."

1 | TOWARD CLIMATE ADAPTATION AND RESILIENCE

There appears to have been a recent tipping of the scales in terms of how we discuss climate change. Whereas in the past the conversation seemed to largely focus on greenhouse gas mitigation, recently climate adaptation has become a major part of the discussion (Wang, Zhao, & Wang, 2018). Making sense of climate adaptation is now common discourse among cities, infrastructure agencies, private industry, and the military. What caused the increased emphasis on climate adaptation is an important question. Global climate is changing rapidly compared to natural variation that has occurred throughout Earth's history, and extreme events such as hurricanes, flooding, wildfires, and heatwaves appear to be exacerbated by a warming world (USGCRP, 2018). Or maybe it is pessimism about our inability to quickly and significantly decrease greenhouse gas emissions, despite decades of research showing us how decreases can happen (Ge, Lebling, Levin, & Friedrich, 2019). Whatever the cause, what is clear is that the global community is rightfully trying to figure out how climate impacts, big or small, should be prepared for, and what they mean for the future of the planet.

As the scale, scope and complexity of climate change becomes clearer, concepts around *resilience* have also come to the forefront of discourse. Whether climate adaptation and resilience are synonymous, or partially overlapping, remains a subject of debate (Nelson, 2011). Resilience principles have been studied for many topics beyond climate adaptation and often have a commonality of capabilities for adaptive capacity and transformation under foreseen and unforeseen conditions (Béné et al., 2018; Meerow, Newell, & Stults, 2016; Woods, 2017). Adaptive capacity is a function of many variables related to sociological, ecological, and technological systems and the relationships between those systems. Resilience frameworks describe a system's ability to thrive when confronted by hazards that it was designed to address and, maybe more importantly, hazards that were not considered (Woods, 2017). The current interest in climate adaptation and resilience is likely not coincidental and transcends climate change concerns. Resilience is becoming a popular concept in many fields at a time when the acceleration and uncertainty of human and natural systems is growing, producing complexities that we are just beginning to recognize (Janssen, Schoon, Ke, & Börner, 2006; Meerow & Newell, 2019; Steffen, Broadgate, Deutsch, Gaffney, & Ludwig, 2015).

The world appears to be accelerating (Kurzweil, 2004; Steffen et al., 2015) and becoming less predictable (Milly et al., 2008) and, at the dawn of the Anthropocene, resilience principles may be of increasing interest to address the challenge of how we approach human systems in an increasingly complex world. Technology (in particular cyber and biotech), demands for services, and perturbations (including climate change) appear to be each becoming more unpredictable (Chester & Allenby, 2019a, 2020). And many of the systems that we have come to rely upon (namely critical infrastructure) have become so complex that our ability to manage them and understand how they'll perform when disturbed is diminishing (Arbesman, 2017). Add in political and ideological polarization and state-sponsored whole society conflict (enabled by rapidly advancing information and communication technologies that we are increasingly integrating into infrastructure) (Allenby, 2015; Lee, 2015) and it should not come as a surprise that resilience, the capacity to adapt, is of interest in helping us navigate the morass.

The competencies needed to manage the increasingly complex landscape of human and natural systems in the Anthropocene are going to be very different than those that we have trained for in the past (Chester & Allenby, 2019a, 2019b; Chester, Markolf, & Allenby, 2019). The accelerating integration of cyber technologies in physical systems, the ability to work across an increasing number of stakeholders with differing viewpoints—many informed by social media that has been curated by artificial intelligence—and the capability to make sense of how infrastructure with layers and layers of technology will respond when perturbed, are just a few of the capabilities that we will need (Chester & Allenby, 2020). Others, like how artificial intelligence will transform how technologies work and people demand services, represent radical shifts in how people understand

and interact with each other, and demand services. Yet as this complexity emerges, we continue to train for and manage our systems largely based on principles rooted in the past, when there was greater stability.

Industrial ecology's emergence decades ago was an effort to make sense of the relationships between human systems and the natural environment. By unpacking these relationships, major insights were created into how humans took from the natural environment, transformed resources into desirable and undesirable products, and put things back into the environment. Remarkable insights into how we managed human systems and could change our approaches to reduce impacts were developed. In doing so major methodological advances were established in areas such as material flow analysis (MFA), life cycle assessment (LCA), input–output analysis (IOA), and urban metabolism. Over time the sophistication and scale of these techniques increased, partly enabled by the computing and data age. Entire cities, regions, and even countries were analyzed (aan den Toorn, Worrell, & van den Broek, 2019; Weinzettel, Vačkářů, & Medková, 2019; Yeow & Cheah, 2019). Remarkable advances in data science were harnessed by the industrial ecology community to develop insights that would not have been possible only a decade before (Meinrenken, Sauerhaft, Garvan, & Lackner, 2014). These techniques in many ways still represent the foundation for how industrial ecologists approach problems, and there is a growing recommendation that climate change and many concurrent challenges represent levels of complexity where conventional approaches are often insufficient (Allenby, 2007).

Climate change has been a major focus of industrial ecology from its inception. A search across the *Journal of Industrial Ecology* archives produces 448 articles that contain the term *greenhouse gas emissions* and only 35 with *climate adaptation* or *climate change adaptation* (Google Scholar keyword search on February 11, 2020). Greenhouse gas emissions-related articles appeared as early as the journal's inaugural year (1997) while climate adaptation articles do not appear until 2011. Industrial ecologists have become leaders in understanding how and why greenhouse gases are emitted, and what effects technologies and policies will have toward mitigating them. Greenhouse gas mitigation might always be the preferred approach to combating climate change—perhaps until our perceptions on geoengineering change—but without any indication that the rate of emissions releases is going to radically change anytime soon there is need to examine the role of climate adaptation science in industrial ecology. Industrial ecologists should confront the question of what competencies are needed to contribute to the climate adaptation discussion and how existing capabilities can be positioned to support new science.

2 | EMERGING PERSPECTIVES FOR INDUSTRIAL ECOLOGY AND CLIMATE ADAPTATION

This special issue was developed to advance thinking on how industrial ecology can support climate adaptation. The issue was developed by a diverse team of industrial ecologists from across the globe, with varying interests and expertise. The guest editorial team included Bhavik Bakshi (Department of Chemical and Biological Engineering, The Ohio State University, USA), Tim Baynes (Commonwealth Scientific and Industrial Research Organisation, Australia), Lynette Cheah (Engineering Systems and Design program, Singapore University of Technology and Design, Singapore), Sybil Derrible (Department of Civil and Materials Engineering, University of Illinois at Chicago), Matthew Eckelman (Department of Civil and Environmental Engineering, Northeastern University, USA), Oliver Heidrich (School of Engineering, Newcastle University, UK), Beibei Liu (Department of Environmental Planning and Management, Nanjing University, China), and Constantine Samaras (Department of Civil and Environmental Engineering, Carnegie Mellon University, USA), and was led by Mikhail Chester (Department of Civil, Environmental, and Sustainable Engineering, Arizona State University, USA). To elicit perspectives across conceptual and pragmatic fronts, a two-tier approach was used. First, the editorial team identified five critical topics and invited established industrial ecology leaders to provide Forum (perspective) articles on those topics. The Forum article authors were given significant creative latitude. Second, a solicitation was opened to the industrial ecology community to provide "proof-of-concept" articles showcasing approaches, methods and tools that the community is already using for climate adaptation. The contributions represent the tip of the iceberg for how the field can begin to support climate adaptation. But collectively they help illuminate a path for future contributions and development.

2.1 | Perspectives

The Forum articles cover diverse domains including financial risk, urban systems, resource scarcity, agriculture, and migration, generally first framing the limitations of current industrial ecology approaches to support climate adaptation, and second providing perspective on how and to what extent industrial ecology can support adaptation in the future. First, to explore how climate adaptation has evolved in the industrial ecology literature, Dayeen, Sharma, and Derrible (2020) developed a bibliometric text mining analysis of the field from 1990 across major publishers. They find that climate adaptation related articles are indeed on the rise while articles focused on more traditional industrial ecology topics such as pollution are in decline. They also identify an increasing cooccurrence of topics with climate adaptation and owe this trend to the multifaceted nature of the problem. The other perspectives articles tackle specific issues in the field. Busch (2019) argues that industrial ecology traditionally takes an inside-out view of systems, where a firm will ask what their impact or resource constraints are and use frameworks such as LCA to assess. He argues that climate adaptation and financial risk require an outside-in view, encompassing exogenous factors. He goes on to catalogue industrial ecology tools and concepts, describing their limitations and usefulness in supporting climate risk assessment. Bleischwitz (2019), Bristow and Mohareb (2019), and Kendall and Spang (2019) focus on particular systems (mineral resource, urban, and agriculture, respectively) to explore unique challenges related to industrial ecology and adaptation. Bleischwitz describes how climate adaptation is a two-way challenge for mineral resource systems in that resources will be needed to support adaptation strategies, and how resource use has implications for adaptation. Bristow and Mohareb argue that the conventional urban metabolism approach for analyzing cities is severely limited in its ability to analyze and support adaptation. They argue that biological systems have innate (e.g., physical, chemical, and nonadaptive processes) and adaptive (ability to learn) capabilities and analyzing urban systems as a function of both is needed, whereas industrial ecology tends to focus on the former. Kendall and Spang provide a critical examination of agriculture arguing that industrial ecology has tended to focus on how systems contribute to climate change, but has neglected how systems are impacted. They provide recommendations for how existing industrial ecology tools can be augmented to do both. Yang, Liu, Wang, Chen, and Smith (2020) discuss the methods and systems-oriented perspective at the heart of industrial ecology, and how they are well-positioned to support adaptation efforts in developing regions. Last, Andrews (2020) takes on the challenge of framing industrial ecology for climate migration. He argues that industrial ecology often removes the critical context that is necessary to understand why and how migration will occur. He lays out several important issues that will affect migration including demographics, urban versus rural, and reemergent nationalism, all of which he connects to existing industrial ecology approaches and introduces questions for the industrial ecology community to address.

An emergent theme from the Forum articles is complexity, or, more so that reductionist approaches within industrial ecology are insufficient to address climate adaptation. The authors advocate for more sophisticated approaches including embracing the analysis of social and political processes, the inclusion of complex dynamics and uncertainty of climate change, and the need for understanding adaptive capacities. The authors do not argue that conventional industrial ecology tools are obsolete, but rather elucidate pathways by which these tools can support more complex thinking as it relates to climate adaptation. The special issue application-focused articles provide first steps toward operationalizing industrial ecology thinking and tools for climate adaptation solutions.

2.2 | Approaches, methods and tools

The application papers reposition existing industrial ecology approaches to support a diversity of climate adaptation questions, and in doing so provide proof-of-concept for some of the recommendations made by the Forum article authors. First, Qiao et al. (2019) and Guest, Zhang, Maadani, and Shirkhani (2019) each use LCA to analyze pavements in different adaptation contexts. Qiao et al. use life cycle costing to analyze hardening strategies in upgrading pavements for hotter temperatures, incorporating future climate projects. Guest et al. use LCA, design models, and deterioration models to develop a framework by which climate impacts to infrastructure can be modeled, thereby supporting redesign for adaptation. Symmes et al. (2019) adapt material flow analysis to assess the vulnerability of a region's resources to climate change related natural disasters. The contributions by Bozeman, Bozeman, and Theis (2019) and Stadler and Houghton (2019) push industrial ecology approaches to acknowledge other domains to address climate adaptation challenges. Bozeman et al. extend LCA of the food–energy–water nexus to include demographics, showing disparities in food, energy, and water impacts by different groups, and providing important information toward building consensus around developing adaptation strategies. Stadler and Houghton make parallel arguments to Bristow and Mohareb, that industrial ecology has much to learn from biological adaptation processes. Susca and Pomponi (2020) show how LCA can be used to bridge built environment and local climate effects. Finally, Chandra-Putra and Andrews (2019) tackle financial risk associated with climate disasters by developing a pricing model and describe the value of integrating such a model next to more conventional industrial ecology urban data and approaches.

3 | PATH FORWARD

The special issue represents the beginning of what should be a larger discussion of how the industrial ecology community can support the climate adaptation space. The articles show ways in which established industrial ecology approaches can shift from the mitigation to adaptation realms. They cover diverse topics and scales, including how approaches to addressing adaptation may differ in developed versus developing regions. There remains, however, much unexplored terrain in the adaptation space. Can industrial ecology help transition human systems from complicated to complex, to address the accelerating and uncertain conditions that include climate *and* other variables such as emerging and disruptive technologies, political and cultural change, service demand changes? And how should industrial ecology integrate with emerging fields of climate study such as decision-making under deep uncertainty, robust decision-making, safe-to-fail, and social–ecological–technological solution framing (Dittrich, Wreford, & Moran, 2016; Grabowski et al., 2017; Kim, Chester, Eisenberg, & Redman, 2019; Shortridge & Camp, 2019; Walker, Lempert, & Kwakkel, 2013)? These key areas remain unexplored and are critical to addressing the emerging dynamics inherent in the Anthropocene.

The compendium of work in the special issue provides first steps toward positioning the field for leadership in a problem space that the industrial ecology community has been wholly invested in preventing since its inception.

ORCID

Mikhail V. Chester https://orcid.org/0000-0002-9354-2102

Mikhail V. Chester

Metis Center for Infrastructure and Sustainable Engineering, School of Sustainable Engineering and the Built Environment, Arizona State University, Tempe, Arizona

Correspondence

Mikhail V. Chester, 660 South College Avenue, Arizona State University, Tempe, AZ 85287-3005.
Email: mchester@asu.edu

Funding information

Time and effort for work on the special issue were in part supported by the U.S. National Science Foundation's Urban Resilience to Extreme Events Sustainability Research Network and Growing Convergence Research programs (award numbers 1444755 and 1934933).

REFERENCES

aan den Toorn, S. I., Worrell, E., & van den Broek, M. A. (2019). Meat, dairy, and more: Analysis of material, energy, and greenhouse gas flows of the meat and dairy supply chains in the EU28 for 2016. *Journal of Industrial Ecology*, 1–14. https://doi.org/10.1111/jiec.12950

Allenby, B. (2007). Earth systems engineering and management: A manifesto. *Environmental Science & Technology*, *41*(23), 7960–7965. https://doi.org/10.1021/es072657r

Allenby, B. R. (2015). The paradox of dominance: The age of civilizational conflict. *Bulletin of the Atomic Scientists*, *71*(2), 60–74. https://doi.org/10.1177/0096340215571911

Andrews, C. J. (2020). Toward a research agenda on climate-related migration. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.13005

Arbesman, S. (2017). *Overcomplicated: Technology at the limits of comprehension*. New York, NY: Penguin.

Béné, C., Mehta, L., McGranahan, G., Cannon, T., Gupte, J., & Tanner, T. (2018). Resilience as a policy narrative: Potentials and limits in the context of urban planning. *Climate and Development*, *10*(2), 116–133. https://doi.org/10.1080/17565529.2017.1301868

Bleischwitz, R. (2019). Mineral resources in the age of climate adaptation and resilience. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12951

Bozeman, J. F., Bozeman, R., & Theis, T. L. (2019). Overcoming climate change adaptation barriers: A study on food-energy-water impacts of the average American diet by demographic group. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12859

Bristow, D. N., & Mohareb, E. A. (2019). From the urban metabolism to the urban immune system. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12919

Busch, T. (2019). Industrial ecology, climate adaptation, and financial risk. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12938

Chandra-Putra, H., & Andrews, C. J. (2019). An integrated model of the real estate market responses to coastal flooding. *Journal of Industrial Ecology*, https://doi.org/10.1111/jiec.12957

Chester, M. V., & Allenby, B. (2019a). Toward adaptive infrastructure: Flexibility and agility in a non-stationarity age. *Sustainable and Resilient Infrastructure*, *4*(4), 173–191. https://doi.org/10.1080/23789689.2017.1416846

Chester, M. V., & Allenby, B. (2019b). Infrastructure as a wicked complex process. *Elementa: Science of the Anthropocene*, *7*(1), 21. https://doi.org/10.1525/elementa.360

Chester, M. V., & Allenby, B. R. (2020). Perspective: The Cyber Frontier and Infrastructure. *IEEE Access*, *8*, 28301–28310. https://doi.org/10.1109/access.2020.2971960

Chester, M. V., Markolf, S., & Allenby, B. (2019). Infrastructure and the environment in the Anthropocene. *Journal of Industrial Ecology*, *23*(5), 1006–1015. https://doi.org/10.1111/jiec.12848

Dayeen, F. R., Sharma, A. S., & Derrible, S. (2020). A text mining analysis of the climate change literature in industrial ecology. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12998

Dittrich, R., Wreford, A., & Moran, D. (2016). A survey of decision-making approaches for climate change adaptation: Are robust methods the way forward? *Ecological Economics*, *122*, 79–89. https://doi.org/10.1016/j.ecolecon.2015.12.006

Ge, M., Lebling, K., Levin, K., & Friedrich, J. (2019). *Tracking progress of the 2020 climate turning point*. Washington, DC: World Resources Institute.

Grabowski Z. J., Matsler A. M., Thiel C., McPhillips L., Hum R., Bradshaw A., Miller T., Redman C. (2017). Infrastructures as socio-eco-technical systems: Five considerations for interdisciplinary dialogue. *Journal of Infrastructure Systems*, *23*(4), 02517002. https://doi.org/10.1061/(asce)is.1943-555x.0000383

Guest, G., Zhang, J., Maadani, O., & Shirkhani, H. (2019). Incorporating the impacts of climate change into infrastructure life cycle assessments: A case study of pavement service life performance. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12915

Janssen, M. A., Schoon, M. L., Ke, W., & Börner, K. (2006). Scholarly networks on resilience, vulnerability and adaptation within the human dimensions of global environmental change. *Global Environmental Change*, *16*(3), 240–252. https://doi.org/10.1016/j.gloenvcha.2006.04.001

Kendall, A., & Spang, E. (2019). The role of industrial ecology in food and agriculture's adaptation to climate change. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12851

Kim, Y., Chester, M. V., Eisenberg, D. A., & Redman, C. L. (2019). The infrastructure trolley problem: Positioning safe-to-fail infrastructure for climate change adaptation. *Earth's Future*, *7*, 704–717. Retrieved from https://agupubs.onlinelibrary.wiley.com/doi/abs/10.1029/2019EF001208

Kurzweil, R. (2004). The law of accelerating returns. In C. Teuscher (Ed.), *Alan turing: Life and legacy of a great thinker* (pp. 381–416). Berlin, Germany: Springer. https://doi.org/10.1007/978-3-662-05642-4_16

Lee, F. E. (2015). How party polarization affects governance. *Annual Review of Political Science*, *18*(1), 261–282. https://doi.org/10.1146/annurev-polisci-072012-113747

Meerow, S., & Newell, J. P. (2019). Urban resilience for whom, what, when, where, and why? *Urban Geography*, *40*(3), 309–329. https://doi.org/10.1080/02723638.2016.1206395

Meerow, S., Newell, J. P., & Stults, M. (2016). Defining urban resilience: A review. *Landscape and Urban Planning*, *147*, 38–49. https://doi.org/10.1016/j.landurbplan.2015.11.011

Meinrenken, C. J., Sauerhaft, B. C., Garvan, A. N., & Lackner, K. S. (2014). Combining life cycle assessment with data science to inform portfolio-level value-chain engineering. *Journal of Industrial Ecology*, *18*, 641–651. https://doi.org/10.1111/jiec.12182

Milly P. C. D., Betancourt J., Falkenmark M., Hirsch R. M., Kundzewicz Z. W., Lettenmaier D. P., Stouffer R. J. (2008). Stationarity Is dead: Whither water management? *Science*, *319*(5863), 573–574. https://doi.org/10.1126/science.1151915

Nelson, D. R. (2011). Adaptation and Resilience: Responding to a changing climate. *Wiley Interdisciplinary Reviews: Climate Change*, *2*(1), 113–120. https://doi.org/10.1002/wcc.91

Qiao, Y., Santos, J., Stoner, A. M. K., & Flintsch, G. (2019). Climate change impacts on asphalt road pavement construction and maintenance: An economic life cycle assessment of adaptation measures in the State of Virginia, United States. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12936

Shortridge, J., & Camp, J. S. (2019). Addressing climate change as an emerging risk to infrastructure systems. *Risk Analysis*, *39*(5), 959–967. https://doi.org/10.1111/risa.13234

Stadler, F., & Houghton, L. (2019). Breathing life into climate change adaptation. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12922

Steffen, W., Broadgate, W., Deutsch, L., Gaffney, O., & Ludwig, C. (2015). The trajectory of the Anthropocene: The Great Acceleration. *The Anthropocene Review*, *2*(1), 81–98. https://doi.org/10.1177/2053019614564785

Susca, T., & Pomponi, F. (2020). Heat island effects in urban life cycle assessment: Novel insights to include the effects of the urban heat island and UHI-mitigation measures in LCA for effective policy making. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12980

Symmes, R., Fishman, T., Telesford, J. N., Singh, S. J., Tan, S. - Y., & De Kroon, K. (2019). The weight of islands: Leveraging grenada's material stocks to adapt to climate change. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12853

USGCRP. (2018). *Impacts, risks, and adaptation in the United States: Fourth national climate assessment* (Vol. II). Washington, DC: U.S. Global Change Research Program. https://doi.org/10.7930/NCA4.2018

Walker, W. E., Lempert, R. J., & Kwakkel, J. H. (2013). Deep uncertainty. In S. I. Gass & M. C. Fu (Eds.), *Encyclopedia of operations research and management science* (pp. 395–402). Boston, MA: Springer US. https://doi.org/10.1007/978-1-4419-1153-7_1140

Wang, Z., Zhao, Y., & Wang, B. (2018). A bibliometric analysis of climate change adaptation based on massive research literature data. *Journal of Cleaner Production*, *199*, 1072–1082. https://doi.org/10.1016/j.jclepro.2018.06.183

Weinzettel, J., Vačkářů, D., & Medková, H. (2019). Potential net primary production footprint of agriculture: A global trade analysis. *Journal of Industrial Ecology*, *23*, 1133–1142. https://doi.org/10.1111/jiec.12850

Woods, D. D. (2017). *Resilience engineering: Concepts and precepts*. Boca Raton, FL: CRC Press.

Yang, Y., Liu, B., Wang, P., Chen, W. - Q., & Smith, T. M. (2020). Toward sustainable climate change adaptation. *Journal of Industrial Ecology*. https://doi.org/10.1111/jiec.12984

Yeow, L. W., & Cheah, L. (2019). Using spatially explicit commodity flow and truck activity data to map urban material flows. *Journal of Industrial Ecology*, *23*, 1121–1132. https://doi.org/10.1111/jiec.12849