BIG DATA & SOCIETY

Commentary

Big Data & Society
January–June: 1–10
© The Author(s) 2020
DOI: 10.1177/2053951720904871
journals.sagepub.com/home/bds
SAGE

Smart forests and data practices: From the Internet of Trees to planetary governance

Jennifer Gabrys

Abstract

Environments are increasingly becoming technologized sites of data production. From smart cities to smart forests, digital networks are analyzing and joining up environmental processes. This commentary focuses on one such under-studied smart environment, smart forests, as emerging digital infrastructures that are materializing to manage and mitigate environmental change. How does the digitalization of forests not only change understandings of these environments but also generate different practices and ontologies for addressing environmental change? I first analyze smart forests within the expanding area of smart environments, and then discuss five digital practices that characterize smart forests. Based on this analysis, I suggest that forests are not only becoming highly digital environments but also that forests are transforming into technologies for managing environmental change. Smart forest interventions therefore expand the scope of what could count as a technology, especially in the context of data-oriented planetary governance.

Keywords

Smart environments, smart forests, environmental data, environmental change, data practices, planetary governance

Imagine the replanting of a forest. A common image that springs to mind might be of individual cultivators walking a terrain and planting trees by hand. The process can be careful yet slow. While these practices are still important and widespread, start-up drone companies are now developing digital techniques for mass-planting forests from the sky. Working toward the objective of planting a billion trees per year, these technologies are meant to offer rapid and "industrial-scale" reforestation techniques to compensate for industrial-scale deforestation. Forests, digital technologies, and data analytics are shifting in potentially "revolutionary" ways through these new approaches to reforestation and environmental change.

Smart forests are one among many environments that are increasingly becoming technologized sites of data collection, processing, and analysis. Not just drones but also sensors, artificial intelligence, and robots are transforming forest environments in order to manage their environmental contributions through data collection and data analytics. The digital technologies that comprise these smart environments are installed on tree trunks and embedded in forest soil (Figure 1). They are floating airborne through forest canopies, and they are located in distant clouds and servers where data analytics unfold. Forest technologies include unmanned aerial vehicles (UAVs), or drones, for planting trees and monitoring forest fires; sensor networks for monitoring forest processes that (in a play on the "Internet of Things") have been dubbed the "Internet of Trees" (Figure 2); Light Detection and Ranging (LIDAR) scanning for assessing changes in forest structure; machine learning for automating or responding to forest events such as wildfires; remote sensing for detecting changes in forest cover and detecting deforestation in real time; and civic apps, platforms for monitoring forest conditions

Department of Sociology, University of Cambridge, Cambridge, UK

Corresponding author:
Jennifer Gabrys, Department of Sociology, University of Cambridge, Free School Lane, Cambridge CB2 3RQ, UK.
Email: jg899@cam.ac.uk

Figure 1. Experimental forest with sensors, photo by author.

and search engines for contributing to reforestation initiatives.

While these technologies are proliferating, they are also generating new forms of data and social–political impacts that have yet to be extensively researched. In this overview of smart forests, I ask: How does digitalization not only change understandings of environments but also generate different practices and ontologies for addressing environmental change? To address this question, I first look at how smart environments are expanding across multiple different areas. Second, I consider five specific digital practices that are materializing within smart forests, including observation, automation and optimization, datafication, participation, and transformation and regulation, as data-based operations with distinct social–political effects. Third, I consider how the digitalization of forest environments is leading to a condition where forests also begin to *operate as technologies*. In this sense, I further analyze not just how digital technologies are remaking forests but also investigate how forests are *becoming social–political technologies* for addressing environmental change. Forests and the social–political relations that sustain them are shifting so that forests function as technical instruments informed by data that are meant to mitigate and even solve the problem of environmental change. Yet this reworking of forests also involves a reworking of technology toward new conjugations of humans, nonhumans and environments—through digital and data-intensive operations.

Forests are crucial to acting on environmental change. They are key contributors to the carbon cycle and biodiversity, as well as air and water quality. Given the urgency of addressing environmental change, policymakers, scientists, and communities have identified forests as important spaces to conserve and cultivate. Meeting climate targets requires both halting deforestation and contributing to practices of mass-scale reforestation. In this context, forest practices are emerging together with environmental policies and sustainable development goals that attempt to conserve forests as carbon sinks, and to sustain and cultivate forests as green infrastructure. In diverse regions around the world—from Germany to New York City to Thailand—smart forests are now emerging where digital technologies are used to manage, monitor, enhance, and expand these rural and urban spaces in response to environmental change. There are increasing numbers and types of smart forests being developed to address environmental change, at the same time that forests are under threat from deforestation and land use change. This text then considers how these digital and data-based reworkings of forests potentially lead to significant changes in environmental engagement and planetary governance.

Smart environments: From smart cities to smart forests

While there is now extensive research on smart cities and data, other "smart" environments have been less

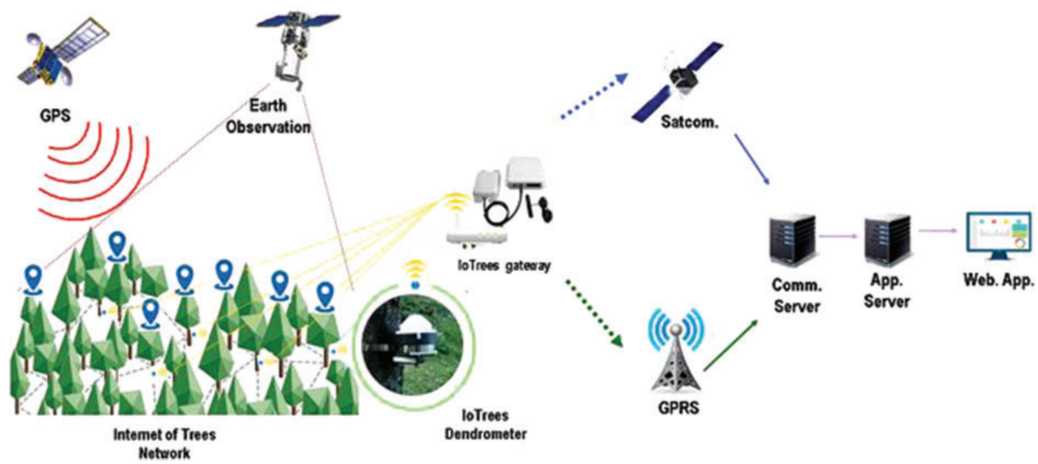

Figure 2. Internet of Trees, European Space Agency.

well studied within the social sciences.[1] Smart cities research has focused on the complex entanglements of digital technologies, governance, and social–political life (Antenucci, 2019; Datta, 2015; Dourish, 2016; Gabrys, 2014b; Marvin et al., 2016; Tironi and Valderrama, 2018). However, environments that are becoming sites for smartification such as forests have yet to be extensively analyzed for their social and political impacts, even when forests have been test sites for developing smart city technologies (Cuff et al., 2008; Gabrys, 2016a; cf. Bakker and Ritts, 2018). For instance, digital technologies facilitate practices oriented toward measurement, data collection, and automation, often by expert or elite actors through processes that can exacerbate inequalities. These dynamics have been extensively studied within online spaces and in relation to economic and racial inequality (Benjamin, 2019; Eubanks, 2017; Noble, 2018), yet are less well understood in relation to the environmental inequalities that materialize or are reinforced, especially in locations that span from the urban to the rural, and from the Global North to the Global South.[2] The influence of emerging digital technologies on the inhabited and social spaces of forests is less well documented. At the same time, diverse types of "forests" can emerge through digital technologies, which differently sense, value, and assess forest processes and relations (Gabrys, 2012). The promissory aspects of the Internet of Trees thus present as many points of consideration as the more comprehensively discussed Internet of Things. Research in this area is needed in order to further establish how these technologies both enable and constrain particular modes of governance and engagement with forests. Without this research, the development of smart environments such as smart forests runs the risk of producing social–political inequities and undemocratic governance, as has been identified with smart cities (Shelton et al., 2015; Zook, 2017).

Smart cities literature has demonstrated how the digital rewiring of environments has consequences for the experience, governance, and organization of smart urban environments (Bulkeley et al., 2016; Luque-Ayala and Marvin, 2015; Rose, 2017). Furthermore, "smart" is a contested term, operationalized by technology companies, governments, NGOs, and community groups to advance distinct development or governance agendas (Hollands, 2008; cf. Dalton et al., 2019; Schick and Winthereik, 2013). The proliferation of smart technologies, infrastructures, and initiatives can shift the locus of governance from often local or urban governmental actors to more remote and global corporate actors that control technologies and networks, thereby transforming governance and participation (Barns et al., 2017; Meng and DiSalvo, 2018; Shelton and Lodato, 2019). While some insights from smart cities and smart infrastructure literature are transferrable to an understanding of wider smart environments, there also are numerous unstudied effects and transformations that are unique to these locations. By focusing on overlooked environments, technologies, and communities, research on smart environments such as forests can investigate what "smart" as a concept and development framework operationalizes within a wider range of locations.

Such research can also address how planetary governance, democratic engagement, and environmental processes and relations are transformed through these technologies. These transformations can have deleterious consequences that are obscured by techno-optimistic narratives that promote connecting technology with "nature" at a "planetary scale." Technology companies, along with researchers, are beginning to focus more centrally on developing digital solutions to environmental problems, from "AI for Earth," to the Internet of Trees for sensor-based forest management (Joppa, 2017; Microsoft, n.d.; World Economic Forum, 2018). Digital technologies are used to monitor forest health and disease, track logging activities, predict changes in forest structure, optimize resource use, and map urban forest networks (Campbell, 2017; Lu et al., 2010). Moreover, the increasing occurrence of forest fires worldwide is now spurring the development of drones, wireless sensor networks, and machine learning to detect and extinguish fires as they occur in real time (Borba Neumann et al., 2018). Smart forestry might even appear to be an augmentation, promotion, and advancement of the smart city, as the controversial Sidewalk Labs development by Alphabet in Toronto has emphasized the benefits of smart ecosystems as part of its smart urban infrastructures (cf. Nitoslawskia et al., 2019).

In this way, digital technologies are often presented as necessary if unproblematic tools for meeting ambitious environmental objectives, including climate change targets that are often more planetary in scope. For instance, the 2011 Bonn Challenge associated with the International Union for Conservation of Nature (Dave et al., 2017) and the New York Declaration on Forests (2014) have expressed a commitment to restore 150 million hectares of deforested and degraded land worldwide by 2020, and 350 million hectares by 2030. However, this objective would require planting an estimated 300 billion trees in less than two decades. Drone companies are therefore developing "precision forestry" techniques to undertake mass aerial planting of billions of trees per year to meet climate objectives.[3] Yet the locations and communities that would be involved in these practices are often underspecified when focusing on forests as a problem of metrics, data, and digital devices. At the same time, reforestation initiatives are at turns promoted and critiqued, and often the contestations over the benefits of these measures are based on environmental data that is meant to prove or question whether the preservation or augmentation of forests will have its stated effects, irrespective of communities' social–political engagement with these forests.[4]

Many of these assessments of environmental change, along with mitigating actions to be taken, are based on environmental datasets that translate into practices of environmental management and planetary governance (see also Gabrys, 2016b). These practices are based on intersecting and expanding environmental datasets that present the problem of environmental change through a particular set of metrics that in turn legitimate specific technological interventions to meet targets for averting environmental catastrophe. Such practices could be oriented toward planetary governance objectives for meeting climate change targets, but could lead to less responsive governance practices in actual forest contexts. Moreover, while they can potentially introduce new and additional problems for social–political inequality related to environments and land use, these same technologies can also contribute to the very problem of environmental change that they would avert by requiring significant energy and material resources for computer hardware and data processing (Dobbe and Whittaker, 2019; Gabrys, 2011, 2014a). The increased production of data, as well as advancement in data analytics and automation, are promoted as strategies for more effectively managing forest ecosystems (Pinho et al., 2018). Decisions can be taken about how to manage forests based on digital systems—indeed these decisions are seen to be "less vulnerable to politicization" (Joppa, 2017). Yet as extensive research in digital social research and science and technology studies demonstrates, the use of digital technologies does not elide politics, but rather can inform and extend politics into new engagements. The following section identifies five key digital practices that are materializing for forest management and planetary governance that give rise to pressing social–political concerns.

Digital practices for governing environmental change

From cryptocoin for forest protection to contestations over satellite data tracking Amazon deforestation, through to sensor networks forming an Internet of Trees, forests are transforming through digital technologies for addressing environmental change. I outline here how these social–political effects include digital practices of observation (Benson, 2010; Helmreich, 2009; Lehman, 2018), automation and optimization (Mackenzie, 2017; Stacey and Suchman, 2012), datafication (Lippert, 2016; Nafus, 2016), participation (Isin and Ruppert, 2015), and technological regulation and transformation (Ascui et al., 2018). By attending to these transforming intersections of environments, data, digital technologies and social life, it might be possible to more fully identify and address the consequences of smartification as a response to the planetary crisis of environmental change.

Observation

There are numerous ways that digital technologies have contributed to the observation of forests. Some of these practices are not new, with remote sensing of forests having taken place for many decades now. However, the scale of observation, along with the fusion of remote sensing with additional and new digital technologies, is contributing to what is arguably a transformed condition of planetary and forest observation (cf. Goldstein, 2019; Loukissas, 2016; Nadim, 2016). Because forests are increasingly situated as key resources to preserve and manage, environmental change objectives are driving the demand for new technologies of observation to ensure the integrity of forests. For instance, because up to 80% of deforestation has now been attributed to corporate supply chains, there are an increasing number of digital technologies from remote sensing to blockchain that are used to monitor, scan, and validate supply chains of forest-intensive products, including timber as well as palm oil, soy, and beef (cf. Howson et al., 2019). Through the use of such observational technologies, however, forests might primarily become visible as stores of timber or carbon sinks, but not as sites that sustain cultural narratives or indigenous cosmologies. In other words, observational technologies could always already assume that the forest is a *resource* to be managed (de la Cadena 2015).

The introduction, expansion, and interconnection of observational technologies within forest environments—whether through remote sensing, ubiquitous computing, or supply-chain monitoring—raise the question of how smart forests emerge as particular developments for managing environmental change and policy. From forest sites in Brazil, Paraguay, to Indonesia and Thailand, the ways that forests are observed also informs how they are governed and managed—not just for environmental change objectives but also for resource extraction. Observational technologies of tracking and tracing specifically configure, as well as propose, ways of acting on forests (Björk et al., 2011). Technologies and techniques for observing deforestation mobilize and legitimate distinct actors to address this problem, while multiple other actors are often excluded from these same sites of social–political relevance and action. Observation is further entangled with strategies such as transparency and auditing (Ananny and Crawford, 2018; Asdal, 2008; Ballestero, 2012), which are proposed as ways to better manage the problem of deforestation but that also present distinct limits to the actors and practices that might be involved in evidentiary techniques. The analysis of observational technologies and networks is then a key area of study for understanding how forests become a global environmental problem through specific observational practices, as well as the social–political effects of these environmental data practices.

Automation and optimization

Forest fires are now increasingly common around the world, and the surge in fire frequency and intensity has been attributed to climate-change related factors. In response, technologies for detecting and suppressing fires have emerged that use artificial intelligence, infrared video, image software, wireless sensor networks, and UAVs to detect and manage fires. Digital technologies are now becoming automated and optimized components within forest ecosystems. At the same time, the management of fire landscapes has direct consequences for communities living in forests and forest-edge landscapes. The distribution and ongoing operation of these digital infrastructures can influence forest land-use activities and have differential effects for communities that may benefit to greater or lesser degree from these warning and mitigation systems if deployed at scale.

From locations spanning the northern boreal forests to the Mediterranean to the western areas of North America, automation and optimization techniques are being developed to manage environmental change in the form of increased fires. The consequences of automating forest management functions in these ways, however, have not been studied in detail. The development and installation of monitoring technologies will raise questions about who organizes and runs these networks, and how data is gathered, stored, and operationalized. Techniques of automation and optimization could align or conflict with existing forest practices across stakeholder groups, from scientists to community groups and citizen scientists, and create power imbalances around the digital forest practices that are implemented. Smart forest projects using artificial intelligence, wireless sensor networks, and UAVs to detect and manage real-time forest events especially in the form of forest fires demonstrate how distinct decisions are made about what to automate and optimize—and that these are not de-politicized decisions, but rather emerge as differently configured political engagements that span machine logics, data analytics, situated forests practices, policy, and environmental change. Moreover, as the processes of artificial intelligence change through ongoing engagement with these environments, different social–political encounters emerge as they are informed by digital operations. These practices also register within a securitization of environments, where the tracking and tracing operations of drones (Suchman et al., 2017) and the distinct regimes of local, national, or planetary governance, security, and control that these technologies generate (Kaplan and Parks, 2017) become central to the management of environmental change.

Datafication

Forests are now sites of intensive data production. Not only do they generate data from advancing practices of earth observation but also they are locations where sensors, LIDAR, and other data-generating technologies such as Internet of Trees networks monitor environmental conditions. Real-time data from these installations is meant to allow for an immediate understanding of forest dynamics, which in turn are meant to provide an indication of related events in nearby environments. Data becomes a distinct object and tool of governance, where environmental processes and entities are increasingly datafied in order to address environmental change. Forest-specific data analytics such as "Treemetrics" are meant to offer new techniques for resource management, environmental governance, and decision-making. And datafied social networks present new data-oriented ways to facilitate care for forest spaces. In these conjugations of "trees, people and data" (Svendsen and Gunther, 2016), new approaches to land management then occur through mapping and analyzing forest-related networks.

Decisions about what to measure and monitor, the formation of evidence in support of environmental change objectives, and the extent to which this data is able to effect change are part of a complex set of social–political struggles about how to make forests matter. The production of data in forests is neither self-evident nor is it all-encompassing, since some forests might also be sites of more focused study and attention, while others become less central in science and policy discussions—often depending upon the carbon storage potential of forests (Ehrenstein and Muniesa, 2013; Gabrys, 2009). Yet the use of data technologies and practices in multiple forests worldwide, from Internet of Things (IoT) to data analytics and carbon emissions monitoring, are informing how environmental change objectives are formed and addressed. Distinct digital practices transform forests into data in order to act on environmental change. (cf. Latour, 1999; Walford, 2012). Yet as often as not, these practices leave out accounts of environments that do not fit with prevailing modes of research, governance, or social–political interaction (Bowker, 2000; Lippert, 2015). The politics of expertise that emerge through the datafication of forests can also influence whether citizen data is able to register as an alternative or admissible form of evidence, and whether diverging governance objectives can co-exist. The struggles that emerge over data in and about forests are not merely a matter of creating a more comprehensive account of environmental processes. Instead, they can challenge the social–political conditions and cosmologies by which forests come to be relevant (cf. Verran, 2002). By analyzing the social and political consequences of the increasing datafication of forests (Turnhout et al., 2013; cf. Couldry and Yu, 2018), it might be possible to attend to how emissions inventories, resource metrics, and related policy instruments align or conflict with community processes for valuing and evaluating forests.

Participation

From platforms such as Global Forest Watch and open-source software such as I-tree, as well as deforestation alerts and hotlines, and participatory mapping of forest boundaries using GPS and Open Street Map to establish community rights, there are a number of technologies emerging that are meant to enable participation with forests and forest protection. In addition, civic apps and search engines variously provide mechanisms to support reforestation measures, from the Treedom platform for supporting tree planting and calculating carbon offsets to the Ecosia search engine that donates a portion of profits to reforestation initiatives around the world. Digital technologies are promoting new and forest-specific forms of participation, which also intervene in various ways in forest conditions, thereby redistributing and changing forms of forest governance and engagement.

Whether through deforestation "watch" platforms, apps for reporting illegal logging, or monitoring technologies such as acoustic sensors or camera traps for capturing poaching, participatory technologies make the forest *present, senseable, and actionable* in certain ways, for distinct actors, and through specific datasets. These participatory apps, platforms, and sensing devices are often most oriented toward tracking deforestation, while also supporting and funding reforestation initiatives, through what might be referred to as "mediatized worlds" (Hepp and Krotz, 2014). Such participatory technologies often operate as part of the usual matrix of smart city toolkits, but it is less well understood how they could facilitate or reshape civic engagement with forests and environmental change. These digital modes of engagement could propagate distinct exclusions while enabling or delimiting specific engagements with diverse and situated forest communities (cf. Agrawal, 2001; Brammer et al., 2016). Moreover, while urban forests are on the rise, larger and more remote forests are increasingly engaged with through participatory technologies and practices that facilitate engagement with these often-distant environments. For better or worse, these same dynamics of remote participation could introduce specific regimes of power and politics in the control and management of forests that come to be seen as planetary resources, as occurred recently with the fires in the Amazon. By considering civic technologies for forest engagement within the larger context of environmental participation (Chilvers and Kearnes, 2016; Lane et al. 2011) and planetary governance, it might be possible to consider how digital technologies facilitate or impede distinct modes of participation.

Regulation and transformation

The proliferation of digital technologies within and in relation to forests is now contributing to distinct practices for regulating and transforming these environments. As mentioned at the introduction to this commentary, "precision forestry" that uses UAVs, sensors, computer models, data analytics, and artificial intelligence to expedite reforestation initiatives is one key example of how these initiatives are developing to automate environmental management. The ways that more mass-scale and automated planting might alter environmental engagements is an overlooked area of research. For instance, planting trees is often discussed as a civic project that advances and enhances democratic engagements with environments (Bäckstrand and Lövbrand, 2006; Fisher et al., 2015). It is less clear what the civic or political equivalent of planting trees by drone might be.

Start-up technology companies worldwide are now creating digital devices and data practices for regulating, and in turn, transforming forest environments. Digital technologies such as UAVs and their networks are used in support of reforestation and to respond to specific environmental objectives, policies, and targets that are often formed through practices of planetary governance (cf. Lövbrand and Stripple, 2006). In the process, these practices are organizing approaches to forests as technologies that are meant to offer "natural climate solutions" by optimizing and augmenting forest processes. As digital devices and data practices proliferate in forests spaces, so too do forests transform into environmental infrastructures (Bruun Jensen, 2015) and technologies for responding to and mitigating environmental change. These transformations could generate different relations across human and nonhuman communities, which are activated or affected by these emerging techno-ecologies (Hinchliffe, 2007; cf. Kohn, 2013; Puig de la Bellacasa, 2015). The smart forest becomes at once a space of regulation and transformation. Technologies that would govern these environments in order to address and mitigate environmental change are also transforming them into entities that are meant to operate as technologies. Smart forest technologies and systems thus contribute to the reworking of what a forest is and how it operates. Such a point of orientation could expand existing approaches to smart and digital technologies, while reworking conventional understandings of what counts as a technology, by researching how forests transform into technologies through technical and policy interventions.

Conclusion: Questioning planetary governance through the smart forest

Smart environments are now expanding beyond smart cities to encompass many different milieus, from smart forests to smart oceans and smart agriculture. Technology companies, environmental scientists, and state actors are contributing to the development and expansion of these digital systems often to address the urgent problem of environmental change. But these ambitions also become evident as emerging planetary modes of governance that have yet to be adequately assessed for their social–political effects. Technologies that operate at the "scale" of the planetary can operationalize universal and less accountable interventions into environments (Gabrys, 2018). As a relatively overlooked area within social sciences research, the problem of smart environments and the data that is collected, stored, and operationalized to manage these spaces is one that requires greater attention to the social–political relations and inequalities that emerge with and through these systems, as well as the transformations that occur when environments operate as technologies.

"Smart Forests" is the topic of a larger research project now underway that this text outlines.[5] This project investigates the role of digital devices in reconfiguring forests as socio-technical ecologies by examining the power relations and modes of governance that are generated through digital practices of observation, automation, optimization, datafication, participation, regulation, and transformation. These technologies and operations raise key questions about smart environments as they are developing beyond the smart city, how democratic engagement with environmental change might be extended or limited, and what modes of planetary governance are mobilized in relation to forest spaces, communities and practices. Such a research focus seeks to demonstrate the consequences and possibilities that digital technologies have for new modes of environmental politics and sociality as they develop in response to environmental change.

Acknowledgments

This commentary is based on a proposal for an ERC Consolidator Grant, Smart Forests: Transforming Environments into Social-Political Technologies (866006), which was awarded in December 2019.

Declaration of conflicting interests

The author(s) declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The author(s) disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This study was funded by TBC.

ORCID iD

Jennifer Gabrys https://orcid.org/0000-0001-5545-2459

Notes

1. Smart environment are, however, a long-standing and increasingly popular topic within computer science. For instance, see Cook and Das (2005).
2. Practices of measurement and inequality are well established in relation to forests through analyses of the REDD+ mechanism and other policy measure to prevent deforestation. However, the effects of increasingly digital forms of observation and measurement (as they also scale up to "smart" development projects) in relation to forest environments have yet to be extensively studied. On REDD+, see for example Gupta et al. (2012) and Paladino and Fiske (2017).
3. There are also proposals now to plant a trillion trees. See https://www.trilliontrees.org. Related to the topic of precision forestry is the emerging body of research on "precision agriculture" that is of relevance to this discussion, but for which there is no space to address here.
4. For an example of a critique of reforestation proposals, see http://www.realclimate.org/index.php/archives/2019/07/can-planting-trees-save-our-climate.
5. Smart Forests, https://smartforests.net.

References

Agrawal B (2001) Participatory exclusions, community forestry, and gender: An analysis for South Asia and a conceptual framework. *World Development* 29(10): 1623–1648.

Ananny M and Crawford K (2018) Seeing without knowing: Limitations of the transparency ideal and its application to algorithmic accountability. *New Media & Society* 20(3): 973–989.

Antenucci I (2019) The making of urban computing environments: Borders, security and governance. *Synoptique* 8(1): 54–64.

Ascui F, Haward M and Lovell H (2018) Salmon, sensors, and translation: The agency of big data in environmental governance. *Environment and Planning D: Society and Space* 36(5): 905–925.

Asdal K (2008) Enacting things through numbers: Taking nature into account/ing. *Geoforum* 39(1): 123–132.

Bäckstrand K and Lövbrand E, (2006) Planting trees to mitigate climate change: Contested discourses of ecological modernization, green governmentality and civic environmentalism. *Global Environmental Politics* 6(1): 50–75.

Bakker K and Ritts M (2018) Smart earth: A meta-review and implications for environmental governance. *Global Environmental Change* 52: 201–211.

Ballestero A (2012) Transparency short-circuited: Laughter and numbers in Costa Rican water politics. *Political and Legal Anthropology Review* 35(2): 223–241.

Barns S, Cosgrave E, Acuto M, et al. (2017) Digital infrastructures and urban governance. *Urban Policy and Research* 35(1): 20–31.

Benjamin R (2019) *Race after Technology: Abolitionist Tools for the New Jim Code*. Cambridge: Polity Press.

Benson E (2010) *Wired Wilderness: Technologies of Tracking and the Making of Modern Wildlife*. Baltimore, MD: Johns Hopkins University Press.

Björk A, Erlandsson M, Häkli J, et al. (2011) Monitoring environmental performance of the forestry supply chain using RFID. *Computers in Industry* 62(8–9): 830–841.

Bonn Challenge (2011) Available at: www.bonnchallenge.org/content/challenge (accessed 22 November 2019).

Borba Neumann G, Pinheiro de Almeida V and Endler M (2018) Smart forests: Fire detection service. In: *2018 IEEE symposium on computers and communications (ISCC)*. pp. 01276–01279.

Bowker GC (2000) Biodiversity data diversity. *Social Studies of Science* 30(5): 643–683.

Brammer JR, Brunet ND, Burton AC, et al. (2016) The role of digital data entry in participatory environmental monitoring. *Conservation Biology: The Journal of the Society for Conservation Biology* 30(6): 1277–1287.

Bruun Jensen C (2015) Experimenting with political materials: Environmental infrastructures and ontological transformations. *Distinktion: Journal of Social Theory* 16(1): 17–30.

Bulkeley H, McGuirk PM and Dowling R (2016) Making a smart city for the smart grid? The urban material politics of actualising smart electricity networks. *Environment and Planning A: Economy and Space* 48(9): 1709–1726.

Campbell LK (2017) *City of Forests, City of Farms Sustainability Planning for New York City's Nature*. Ithaca: Cornell University Press.

Chilvers J and Kearnes M (eds) (2016) *Remaking Participation: Science, Environment and Emergent Publics*. London: Routledge.

Cook D and Das SK (2005) *Smart Environments: Technology, Protocols and Applications*. Hoboken, NJ: John Wiley & Sons.

Couldry N and Yu J (2018) Deconstructing datafication's brave new world. *New Media & Society* 20(12): 4473–4491.

Cuff D, Hansen M and Kang J (2008) Urban sensing: out of the woods. *Communications of the ACM* 51(3): 24–33.

Dalton C, Wilmott C, Fraser E, et al. (2019) "Smart" discourses, the limits of representation, and new regimes of spatial data. *Annals of the American Association of Geographers*. Available at: https://www.tandfonline.com/doi/abs/10.1080/24694452.2019.1665493

Datta A (2015) New urban utopias of postcolonial India: Entrepreneurial urbanization in dholera smart city. *Dialogues in Human Geography* 5(1): 3–22.

Dave R, Saint-Laurent C, Moraes M, et al. (2017) *Bonn Challenge Barometer of Progress: Spotlight Report 2017*. Gland, Switzerland: IUCN.

de la Cadena M (2015) Uncommoning nature. *E-flux Journal* 65, May–August. Available at: http://supercommunity.e-flux.com/texts/uncommoning-nature/ (accessed 22 November 2019).

Dobbe R and Whittaker M (2019) AI and climate change: How they're connected, and what we can do about it. *Medium,* 17 October 2019. Available at: https://medium.com/@AINowInstitute/ai-and-climate-change-how-theyre-connected-and-what-we-can-do-about-it-6aa8d0f5b32c (accessed 22 November 2019).

Dourish P (2016) The internet of urban things. In: Kitchin R and Perng S-Y (eds) *Code and the City*. London: Routledge, pp.27–46.

Ehrenstein V and Muniesa F (2013) The conditional sink: Counterfactual display in the valuation of a carbon offsetting reforestation project. *Valuation Studies* 1(2): 161–188.

Eubanks V (2017) *Automating Inequality: How High-Tech Tools Profile, Police, and Punish the Poor*. New York: St. Martin's Press.

Fisher DR, Svendsen ES, Connolly J (eds) (2015) *Urban Environmental Stewardship and Civic Engagement: How Planting Trees Strengthens the Roots of Democracy*. London: Routledge.

Gabrys J (2009) Sink: The dirt of systems. *Environment and Planning D: Society and Space* 27(4): 666–681.

Gabrys J (2011) *Digital Rubbish: A Natural History of Electronics*. Ann Arbor, MI: University of Michigan Press.

Gabrys J (2012) Sensing an experimental forest: Processing environments and distributing relations. *Computational Culture* (2). Available at: http://computationalculture.net/sensing-an-experimental-forest-processing-environments-and-distributing-relations/ (accessed 22 November 2019)

Gabrys J (2014a) Powering the digital: From energy ecologies to electronic environmentalism. In: Maxwell R, Raundalen J and Vestberg NL (eds) *Media and the Ecological Crisis*. New York and London: Routledge, pp.3–18.

Gabrys J (2014b) Programming environments: Environmentality and citizen sensing in the smart city. *Environment and Planning D: Society and Space* 32(1): 30–48.

Gabrys J (2016a) *Program Earth: Environmental Sensing Technology and the Making of a Computational Planet*. Minneapolis: University of Minnesota Press.

Gabrys J (2016b) Practicing, materializing and contesting environmental data. *Big Data & Society* 3(2): 1–7.

Gabrys J (2018) Becoming planetary. *e-flux Architecture*. Available at: www.e-flux.com/architecture/accumulation/217051/becoming-planetary (accessed 22 November 2019).

Goldstein JE (2019) The volumetric political forest: Territory, satellite fire mapping, and Indonesia's burning peatland. Antipode. First published: 10 October 2019. Available at: https://doi.org/10.1111/anti.12576 (accessed 22 November 2019).

Gupta A, Lövbrand E, Turnhout E, et al. (2012) In pursuit of carbon accountability: The politics of REDD+ measuring, reporting and verification systems. *Current Opinion in Environmental Sustainability* 4(6): 726–731.

Hepp A and Krotz F (eds) (2014) *Mediatized Worlds: Culture and Society in a Media Age*. London: Palgrave Macmillan.

Hinchliffe S (2007) *Geographies of Nature: Societies, Environments, Ecologies*. London: Sage.

Helmreich S (2009) *Alien Ocean: Anthropological Voyages in Microbial Seas*. Berkeley: University of California Press.

Hollands RG (2008) Will the real smart city please stand up? *City* 12(3): 303–320.

Howson P, Oakes S, Baynham-Herd Z, et al. (2019) Cryptocarbon: The promises and pitfalls of Forest protection on a blockchain. *Geoforum* 100: 1–9.

Isin E and Ruppert E (2015) *Being Digital Citizens*. London: Rowman & Littlefield.

Joppa LN (2017) AI for earth. *Nature* 552(21/28 December): 325–328.

Kaplan C and Parks L (eds) (2017) *Life in the Age of Drone Warfare*. Durham: Duke University Press.

Kohn E (2013) *How Forests Think: Towards an Anthropology beyond the Human*. Berkeley: University of California Press.

Lane SN, Odoni N, Landström C, et al. (2011) Doing flood risk science differently: An experiment in radical scientific method. *Transactions of the Institute of British Geographers* 36(1): 15–36.

Latour B (1999) *Pandora's Hope: Essays on the Reality of Science Studies*. Cambridge: Harvard University Press.

Lehman J (2018) From ships to robots: The social relations of sensing the world ocean. *Social Studies of Science* 48(1): 57–79.

Lippert I (2015) Environment as datascape: Enacting emission realities in corporate carbon accounting. *Geoforum* 66: 126–135.

Lippert I (2016) Failing the market, failing deliberative democracy: How scaling up corporate carbon reporting proliferates information asymmetries. *Big Data & Society* 3(2): 1–13.

Loukissas YA (2016) A place for big data: Close and distant readings of accessions data from the arnold arboretum. *Big Data & Society* 3(2): 1–20.

Lövbrand E and Stripple J (2006) The climate as political space: On the territorialisation of the global carbon cycle. *Review of International Studies* 32(2): 217–235.

Lu JWT, Shane M, Svendsen E, et al. (2010) *MillionTreesNYC, Green Infrastructure, and Urban Ecology: Building a Research Agenda*. New York: City of New York Parks and Recreation.

Luque-Ayala A and Marvin S (2015) Developing a critical understanding of smart urbanism? *Urban Studies* 52(12): 2105–2116.

Mackenzie A (2017) *Machine Learners: Archaeology of a Data Practice*. Cambridge: MIT Press.

Marvin S, Luque-Ayala A and McFarlane C (eds) (2016) *Smart Urbanism: Utopian Vision or False Dawn*? London: Routledge.

Meng A and DiSalvo C (2018) Grassroots resource mobilization through counter-data action. *Big Data & Society* 5(2): 1–2.

Microsoft (n.d.) IoT for natural resources. Available at: https://azure.microsoft.com/en-gb/product-categories/iot/ (accessed 22 November (2019)

Nadim T (2016) Blind regards: Troubling data and their sentinels. *Big Data & Society* 3(2): 1–6.

Nafus D (ed.) (2016) *2016. Quantified: Biosensing Technologies in Everyday Life*. Cambridge: MIT Press.

New York Declaration on Forests (2014) *Climate Summit 2014*. New York: United Nations Headquarters.

Nitoslawskia SA, Galle NG, Van Den Bosch CK, et al. (2019) Smarter ecosystems for smarter cities? A review of trends, technologies, and turning points for smart urban forestry. *Sustainable Cities and Society* 51 (November): 101770.

Noble SU (2018) *Algorithms of Oppression: How Search Engines Reinforce Racism*. New York University Press.

Paladino S and Fiske SJ (eds) (2017) *The Carbon Fix: Forest Carbon, Social Justice, and Environmental Governance*. London: Routledge.

Pinho TM, Coelho JP, Oliveira J, et al. (2018) An overview on visual sensing for automatic control on smart farming and forest management. In: *13th APCA international conference on automatic control and soft computing (CONTROLO)*, Ponta Delgada, Azores, Portugal, 4–6 June 2018. pp.419–424.

Puig de la Bellacasa M (2015) Making time for soil: Technoscientific futurity and the pace of care. *Social Studies of Science* 45(5): 691–716. 2015

Rose G (2017) Posthuman agency in the digitally mediated city: Exteriorization, individuation, reinvention. *Annals of the American Association of Geographers* 107(4): 779–793.

Schick L and Winthereik B (2013) Innovating relations – Or why smart grid is not too complex for the public. *Science & Technology Studies* 26(3): 82–102.

Shelton T and Lodato T (2019) Actually existing smart citizens. *City* online first. Available at: https://www.tandfonline.com/doi/abs/10.1080/13604813.2019.1575115

Shelton T, Zook M and Wiig A (2015) The "actually existing smart city". *Cambridge Journal of Regions, Economy and Society* 8(1): 13–25.

Stacey J and Suchman L (2012) Animation and automation – The liveliness and labours of bodies and machines. *Body & Society* 18(1): 1–46.

Suchman L, Follis K and Weber J (2017) Tracking and targeting: Sociotechnologies of (in)security. *Science, Technology & Human Values* 42(6): 983–1002.

Svendsen E and Gunther B (2016) Stewards of the urban forest. In: *International day of forests and world water day*, 22 March 22, United Nations Audio Visual Library.

Tironi M and Valderrama M (2018) Unpacking a citizen self-tracking device: Smartness and idiocy in the accumulation of cycling mobility data. *Environment and Planning D: Society and Space* 36(2): 294–312.

Turnhout E, Waterton C, Neves K, et al. (2013) Rethinking biodiversity: From goods and services to "living with". *Conservation Letters* 6(3): 154–161.

Verran H (2002) A postcolonial moment in science studies: Alternative firing regimes of environmental scientists and aboriginal landowners. *Social Studies of Science* 32(5–6): 729–762.

Walford A (2012) Data moves: Taking Amazonian climate science seriously. *Cambridge Anthropology* 30(2): 101–111.

World Economic Forum (2018) *Centre for the Fourth Industrial Revolution Network*. Geneva: World Economic Forum.

Zook M (2017) Crowd-sourcing the smart city: Using big geosocial media metrics in urban governance. *Big Data & Society* 4(1): 1–13.