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Perspective Essay

‘Rage against the machine’? The opportunities and risks concerning the automation of urban green infrastructure

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ABSTRACT

Contemporary society is increasingly impacted by automation; however, few studies have considered the potential consequences of automation on ecosystems and their management (hereafter the automation of urban green infrastructure or UGI). This Perspective Essay takes up this discussion by asking how a digital approach to UGI planning and management mediates the configuration and development of UGI and to whose benefit? This is done through a review of key issues and trends in digital approaches to UGI planning and management. We first conceptualize automation from a social, ecological, and technological interactions perspective and use this lens to present an overview of the risks and opportunities of UGI automation with respect to selected case studies. Results of this analysis are used to develop a conceptual framework for the assessment of the material and governance implications of automated UGIs. We find that, within any given perspective, the automation of UGI entails a complex dialectic between efficiency, human agency and empowerment. Further, risks and opportunities associated with UGI automation are not fixed but are dynamic properties of changing contextual tensions concerning power, actors, rules of the game and discourse at multiple scales. We conclude the paper by outlining a research agenda on how to consider different digital advances within a social-ecological-technological approach.

1. Introduction

The effective provision and management of urban green infrastructure (UGI), including urban trees, parks, blue and green open spaces, and green walls and roofs, have the potential to provide both direct benefits (e.g., ecological connectivity and habitat conservation) and a range of co-benefits to urban societies, thereby delivering on the UN 2030 Agenda for Sustainable Development goals and the Habitat III new urban agenda (Bai et al., 2018). Co-benefits include increased air and water quality, improved technological solutions to storm water management, social cohesion, and increased human health and well-being (Kabisch, Qureshi, & Haase, 2015; Raymond et al., 2017). To realize these benefits in the face of accelerating pressures such as climate change and urban densification, scientists and policy makers are now calling for integrated solutions that operate “at the intersection of social, cultural, digital and nature-based innovation” (European Commission, 2017; also see Eggermont et al., 2015).

In parallel, practitioners are progressively utilizing digital solutions for urban greening in efforts to optimize, and in some cases democratize, the delivery and implementation of UGI (Cantrell, Martin, & Ellis, 2017; DiSalvo & Jenkins, 2017). For example, automation is supporting UGI management in lawn care through autonomous lawn mowers (Grossi et al., 2016), urban forest inventories feature digitally-tagged trees that transmit information to smart phone platforms (Luvisi &

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Lorenzini, 2014), biodiversity assessments are undertaken through gaming (Sandbrook, Adams, & Monteferri, 2015), citizen nature preferences are monitored through Instagram images and hash tags (Guerrero, Møller, Olafsson, & Snizek, 2016), and urban foraging is undertaken with community-developed semi-autonomous drones (DiSalvo & Jenkins, 2017). These technologies are driven by government and business aims at productivity (and profitability), but also creativity and innovation coupled with promises of 'smart' and 'real-time' solutions to environmental and societal demands and challenges (Cantrell et al., 2017; Taylor Buck & While, 2017; Gabrys, 2014). Taken together, these examples represent the kind of rapid technological development suggestive of potential disruption in the field of UGI planning and management.

Automation in nature management, including in UGI, shows no signs of slowing based on the demands of politicians and initiatives of citizens for collaborative and participatory urbanism (Gil-Garcia, Helbig, & Ojo, 2014), and the forecasted productivity-enhancing benefits associated with the adoption of automated resource management (Schwab, 2016). Yet, little attention has been paid to the assumptions, opportunities, and especially risks of these technologies in urban societies and the governance of existing UGI. Moving forward, it is critical to consider not only the potential benefits but also the challenges that accompany such profound change, specifically concerns regarding the transparency, fairness, and technical proprietary of autonomous and semi-autonomous UGI (Galaz & Mouazen, 2017).

This Perspective Essay takes up this discussion by asking *how a digital approach to UGI planning and management mediates the configuration and development of UGI and to whose benefit*? Specifically, what are the social, ecological, and technical opportunities and risks of the uptake of computational technologies in UGI delivery and management? This is done through a review of key issues and trends in digital approaches to UGI planning and management. Given the dearth of discussion of automation of UGI in the literature, we first conceptualize automation by building on insights from the digital geographies, sustainable urban transitions, and UGI governance literature. In this section we briefly review digital innovation in natural resource management. We then discuss the potential implications of these trends and issues for the UGI context by drawing on six mini-case studies outlining major themes in UGI planning and management: Case 1 - wildlife and conservation management, Case 2 - urban food production, Case 3- human well-being, Case 4 - legitimation of citizen knowledge/citizen science, Case 5 - citizen stewardship, and Case 6 - governance (Mell, 2016; Van der Jagt et al., 2017). We conclude the paper by establishing a conceptual framework for the assessment of the material and governance implications of automated UGIs outlining a research agenda on how to consider different digital advances within a social-ecological-technological approach.

2. Conceptualizing the automation of UGI

The automation of UGI has social, ecological, and technological ramifications. At present, however, automation is discussed in the natural resource management literature in purely technical and ecological (Cantrell et al., 2017; Luvisi & Lorenzini, 2014) or social and ecological terms (Guerrero et al., 2016; Kahila-Tani, Broberg, Kyttä, & Tyger, 2016). Below, we develop an analytical framework to bridge the various interfaces of the automation of UGI, discussing the interactions amongst technical innovation, social systems, and ecosystem functions. These system interfaces are labeled accordingly as 'ecological-technological', 'social-technological', and 'social-ecological' (also see Table 1). This approach draws on McPhearson et al. (2016)'s conceptualization of UGI as a system made up of social, ecological and technological interactions.

Beyond these interactions, we also conceptualize how UGI automation is coupled to and impacted by (and impacts on) broader governance settings. Governance in this context is referred to as the collective cross-sectoral steering of decision-making and policy as determined by "the rules of the game, power, actors, and discourses" (Arts, Leroy, & van Tatenhove, 2006). We argue that on a broader-scale, automation mediates the social, ecological, and technological interactions in UGI by shifting the formal and informal terms of decision making, rules and regulations. In turn, existing governance contexts will mediate the impact of automation. Power in this case is conceived as the division of resources between actors and institutions, as well as influence over who determines the rules and sets the dominant narrative; discourses relate to the views and narratives of the actors involved in UGI automation (Liefferink, 2006). Dominant discourses determine norms, values, and problem definitions and solutions. Automation is thus conceptualized as multi-scale digital and computational objects, processes, infrastructures, and assemblages (Kitchin & Dodge, 2011).

2.1. Ecological-technological perspective

Automation in natural resource management commonly refers to technical developments in computer hardware and software that make it increasingly possible to remove humans from operational tasks, strategic development, and the execution of simple to complex decision making (Cantrell et al., 2017; Parasuraman, Sheridan, & Wickens, 2000). These interactions are discussed as ecological-technological interactions, whereby technological advancements efficiently contribute to the biophysical cultivation and maintenance of landscapes, from forestry and agriculture to conservation monitoring and management. Robots are deployed for areal seeding and weed control in tropical forests (Elliott, 2016), for the monitoring of vector-borne diseases, plant pests, aquatic pests (Jurdak et al., 2015), and for the collection of water samples in remote areas (Schwarzbach, Laiacker, Mulero-Pazmany, & Kondak, 2014). In agriculture, mobile robots disperse pesticides and herbicides, and produce synthetic foods (Majima, 2014). Robots also support monitoring, for instance of invasive species in harbors (Dunbabin & Marques, 2012), and cover vast territories, as in the case of monitoring the growth and decline of extensive coral reefs (Cantrell et al., 2017). Furthermore, deep machine learning is used to evaluate the qualities and development potential of urban environments (Liu, Silva, Wu, & Wang, 2017). In this interaction, institutional power and agency is held by natural resource managers and or the private sector.

2.2. Social-technological perspective

Yet, the automation of natural resource management is more than semi-autonomous ecological steering; it also encompasses social-technological interactions situated within a proliferating network of digital technology (Kitchin & Dodge, 2011). These social and technological networks (Smith & Stirling, 2010) are supported by ubiquitous computing and digital technology such as wireless broadband, analytical software, real-time sensing and feedback, and the Internet of Things. This social-technological fabric is deployed in our urban infrastructure as a network of information and control systems, providing so-called big data used to respond to large-scale problems of climate change, urbanization, citizen engagement, and resource efficiency (Kitchin, 2014). These interactions monitor and manage real-time urban flows, coupled with the mobile computing (smartphones) of everyday users of the city to generate data regarding e.g. peoples' locations and activities (Kitchin & Dodge, 2011). In a social-technological framing of natural resource management automation, social processes shape the development and use of technology and in turn open up new possibilities for social practices linked to institutionally structured market incentives and consumer demands (Smith & Stirling, 2010).

Such examples of automation relate to social-technical interactions between diverse actors in the conservation and management of natural resources. "Smart" governance platforms support ecosystem planning and place-keeping exercises with citizens providing voluntary geographic information (Kahila-Tani et al., 2016). Nature-recreation apps

Table 1
Summary of the analytical use of social, ecological, technological interactions in the automation of Urban Green Infrastructure (UGI).

Summary of the dimensions of UGI automation		
Perspectives of UGI automation	Material examples	Governance implications
Ecological-technological	Robotic lawn mowers, deep machine learning urban simulations	Potential decrease in human agency in UGI cultivation and development.
Social-technological	Ubiquitous computing and networked digital technology such as "smart" governance platforms and nature recreation apps	The rules, routines, and institutional arrangements of UGI development being iteratively shaped by technological advancements and social practices.
Social-ecological	Technology mediating people, nature, and computational relations such as augmented reality, virtual reality, and deep-learning robots	Technology having progressive or regressive impacts on existing networks of power and human relations to ecological systems.

support GPS-tagged site identification, route mapping, and navigational abilities for hunters, fishing, birding, food foraging, amongst others (Jepson & Ladle, 2015). Nature gaming apps such as Pokémon Go enhance outdoor experiences with interactive augmented reality (AR) scenarios, engaging users in 3D competitive Pokéhunts in public green spaces (Dorward, Mittermeier, Sandbrook, & Spooner, 2016). Citizen science apps crowdsource knowledge to generate community awareness and scientific literacy around environmental management (Newman et al., 2012).

2.3. Social-ecological perspective

Automation also has social-ecological implications in terms of how the software, or code, underpinning computational technology impacts the human relations to ecological processes, configurations, and services (Kitchin & Dodge, 2011). This technological fabric mediates the relationships between human activities and infrastructural and ecosystem processes by opening up new possibilities of perceiving and accessing social-ecological interactions. Here digital tools link provisioning and regulating ecosystem services to human wellbeing by capturing diverse citizen nature perceptions and values. Computational processes augment human and more-than-human agency. This interaction promotes innovation, sensing, and feedback to craft 'intelligent' narratives of community engagement in urban ecosystem resilience (Srivastava & Vakali, 2012). Social ecological interactions may have progressive or regressive impacts on existing networks of power and relations depending on whom has access (to digital tools and networks) and for whose benefit they are developed.

Such social-ecological interactions can support monitoring of diverse perceptions and experiences of nature. Mobile software apps are used to study and enjoy nature typically relating to nature recreation, nature gaming, and citizen science (Jepson & Ladle, 2015). Augmented reality is deployed for "socially-networked" conservation education in museums to digitally model, analyze, and experience endangered species (Keaveney, Keogh, Gutierrez-Heredia, & Reynaud, 2016). Virtual reality simulations of landscapes, such as a forest glade, are accounting for individual emotional experiences and exploratory behavior in outdoor settings (Dobricki & Pauli, 2016). Geo-tagged urban trees are assigned email addresses to monitor citizen values attached to their urban forest (Gulsrud, Hertzog, & Shears, 2018). E-plants, or living plants with implanted polymer wires connected with naturally occurring electrolytes in the plant's tissue, act as electrochemical transistors as well as a 'digital logic gate', basic components of a computer system (Stavrinidou et al., 2017).

2.4. Summary of UGI automation

Uniting these dimensions of automation is the argument that digital technology, through systems, networks, and ways of doing, broadly impacts on the configuration, development, and management of cities and urban regions, including the social, ecological, and technological interactions of urban landscapes (Kitchin & Dodge, 2011; McPhearson et al., 2016). As the automation of UGI progresses, decision makers, citizens, and the private sector will be confronted with questions regarding who governs the configuration and development of digital UGI and whose knowledge and experience count in this debate with respect to different interactions in the system (Table 1). This analytical perspective engages questions of agency and power surrounding the automation of UGI, challenging good story narratives about innovation and technological adaptation in natural resource management (Arts, van der Wal, & Adams, 2015) and opens up for an identification of the opportunities and risks associated with the governance of automated urban ecosystems. To contextualize these opportunities and risks, we first provide some examples where automation is affecting UGI management.

3. Case backgrounds

In this section we draw on six mini-cases to outline key trends in the automation of UGI.

3.1. Case 1: virtual fencing of baboon troops in Cape Town, South Africa

In the increasingly urbanized fringe of Cape Town, virtual fencing is being used by natural resource managers to reduce conflicts between local residents and baboon troops. Virtual fencing combines smart phone, Global Positioning System (GPS), and cloud storage technologies to monitor and move animals (both livestock and wildlife) remotely, without the use of a traditional wire fence. Animals are equipped with a neck collar that emits an audible alarm as a cue for the animal to avoid a subsequent mild electric shock as they approach a virtual fence (Anderson, Estell, Holechek, Ivey, & Smith, 2014). Virtual fencing in Cape Town has successfully reduced human wildlife conflicts by scaring baboons out of human territory where they otherwise actively raid for food in local private gardens and homes (Richardson et al., 2015).

3.2. Case 2: automated vertical farming in Kyoto, Japan

In densely-populated Kyoto, a Japanese company named Spread has launched a new automated indoor vertical farming facility to produce lettuce solely with the aid of robots, drastically reducing labor costs while increasing the nutrient value of the lettuce (Techno Farm, 2017). Automated vertical farming maximizes production while minimizing labor costs by using advanced sensors, LED lighting, and hydroponic systems combined with machine learning to grow crops without sunlight or soil. The technology behind automated indoor vertical farming is currently being marketed at a smaller-scale to urban consumers as high-tech urban farming boxes for use in offices or homes.

3.3. Case 3: automated health monitoring in Duluth, Minnesota, USA

The verdant city of Duluth is an epi-center for automated health monitoring, and has been named the fittest city in America based on citizen-volunteered health data from Fitbit, a mobile software application (Meyers, 2017). Fitbit collects user-volunteered personal health data consisting of daily steps, active minutes, resting heart rate, and sleep duration. Automated health monitoring is based on specific tracking data obtained via sensors in smart phones (for levels of social interaction) and blue-tooth or wi-fi enabled health wearables such as accelerometers (for physical activity or sleep patterns), oximeters built into rings (for heart rate), and electromyography sensors embedded into clothing (for muscle activity) (Piwek et al., 2016). City promoters note Duluth's urban greenspaces, including 160 miles of hiking trails, an expanding network of trail and road bike trails, plus 11,000 acres of open space along miles of Lake Superior's shoreline as key elements in keeping residents active.

3.4. Case 4: youth-driven citizen science in Oakland, California, USA

In Oakland, low-income youth of color have been engaged in citizen science to map, track, and monitor neighborhood access to ecosystem services such as clean water, safe air quality, health care, wellness, transportation, and food access (Akom, Shah, Nakai, & Cruz, 2016). The Mapping to Mobilize (M2M) program draws on point algorithm technology in which youth participants combine paper maps with smart phone geo-tagging to inventory and interpret community environmental and health services. The youth-collected data revealed that East Oakland is a vast food desert lacking well-stocked grocery stores with healthy food, and this awareness subsequently increased youth efforts in urban food production.

3.5. Case 5: automated tree stewardship in Melbourne, Australia

The city of Melbourne is actively working with automated governance tools to integrate local and traditional knowledge into their urban forest strategy (UFS) as they aim to increase their urban tree canopy by 40% by 2040 against the odds of community skepticism and increasingly unpredictable climatic conditions (Kendal & Baumann, 2016). An on-line digital platform called the Melbourne Urban Forest Visual engages citizens in discussions of ecosystem services through an invitation to explore the 'big tree data' of the publically-managed urban forest and collects information from citizens regarding their personal perceptions of trees. This platform informatively guides viewers through the technical principles of the UFS visualizing in images and graphs, tree life span, tree species diversity, and urban canopy cover with and without tree plantings. All data on the platform is open to public perusal and can be accessed via the City of Melbourne's open data portal (City of Melbourne, 2017).

3.6. Case 6: robotic tree-care (early prototype)

Tree-climbing robots are under development to support pruning operations. A Chinese model consists of two vehicles, which are attached on the trunk of a tree and stick tightly on the tree due to a holding device. A tool attached to the end of a long pole serves to perform tasks such as tree maintenance, harvesting and surveillance (Ren, Yang, Yan, & Zhang, 2014). A recent development, inspired by arboreal animals, is an autonomous tree-climbing algorithm that identifies the environment and determines the optimal climbing position. This algorithm enables a robot to explore and climb on an unknown shape of a tree autonomously (Lam & Xu, 2011).

4. Opportunities and risks of automation in the six cases

In this section, we compare opportunities and risks related to the automation of UGI with reference to the six mini-cases across ecological-technological, social-technological and social-ecological interfaces. Here we consider risks and opportunities in relation to elements of the case context.

4.1. Ecological-technological interactions

The ecological-technological context considers how new forms of technology affect elements of food security and ecosystem resilience. Case 2, on automated vertical farming, demonstrates that urban food production is driven by private industry managing for precision farming principles such as reduced water use, fertilizer application, reduced transportation costs, and increased ecological functions (Benis, Reinhart, & Ferrão, 2017). Opportunities arise regarding the potential for increased urban food security in the face of increasingly unpredictable weather and or labor shortages (Benis & Ferrão, 2017), and automated vertical farming may provide an important function by increasing resilience against disasters (earthquakes etc.) (Yokohari, Amati, Bolthouse, & Kurita, 2010). However, indoor farming is largely limited to greens and mushrooms and is not suitable for other crops grown outdoors (Buehler & Junge, 2016). The technology used in automated indoor farming requires minimal human labor and as such, may represent a threat to rural and urban farming traditions, specifically biocultural knowledge (Andersson & Barthel, 2016). Measures of efficiency might dominate, which could be against the will or wishes of both local ecosystem managers and other stakeholders. Automation has been found to homogenize ecosystems, with a decrease in the diversity of plants, animals, and habitats (van Zanten et al., 2014). Additionally, concerns loom regarding the energy-intensive nature of automated vertical indoor farming and consequent carbon emissions (Mills, 2012).

Similar opportunities and risks arise with reference to Case 6, robotic tree care. Tree-climbing robots have the potential to reduce management costs, poor tree-cutting practices, and arborists' injuries. At the same time, they may erode professional ecological knowledge (Bardekjian, 2015) and lead to a loss of intuition and agency of arborists (Bardekjian, 2016). Urban tree care is highly contested as citizens have strong feelings linked to the aesthetics and health of trees (Sandberg, Bardekjian, & Butt, 2014). The automation of urban tree care raises questions of urban forest governance regarding not only citizen consultation but the very role of citizens in the stewardship of urban trees (Lawrence, De Vreese, Johnston, Konijnendijk van den Bosch, & Sanesi, 2013).

4.2. Social-technological interactions

The magnitude and direction of threat or opportunity in this context derives from how automation mediates technological drivers related to efficiency, profit gains, and consumer demands with wider social values such as public health and well-being and stakeholder engagement. Each case example presents different benefits within this context. The automation of food production (Case 2) and the robotic care of urban trees (Case 6) is to a large degree driven by the opportunities of reducing the institutional cost of production by increasing efficiency and output through the replacement of humans with computational power (Bogue, 2016). Similarly Case 3, on automated health monitoring, has the potential to revolutionize approaches to global environmental health policy through efficient, collective and place-based health care (Maturo & Setiffi, 2016). The use of personal Fitbit trackers not only engages individual users in health monitoring, it also increases community awareness of outdoor recreation as an important health opportunity (Meyers, 2017). Case 4, on citizen science demonstrates the opportunity to greatly democratize UGI planning processes by legitimizing diverse local knowledge (Akom et al., 2016). Youth-focused citizen science apps can support environmental education and spark curiosity and community engagement (Ballard, Dixon, & Harris, 2017).

Risks associated with these cases regard quick technological fixes to wide-spread societal problems without addressing the social and economic root of the problem. In automated vertical farming and the robotic care of trees, employment levels are also key to social, cultural and economic resilience, however trends in automation could threaten both specialized and non-specialized UGI labor (Frey & Osborne, 2017).

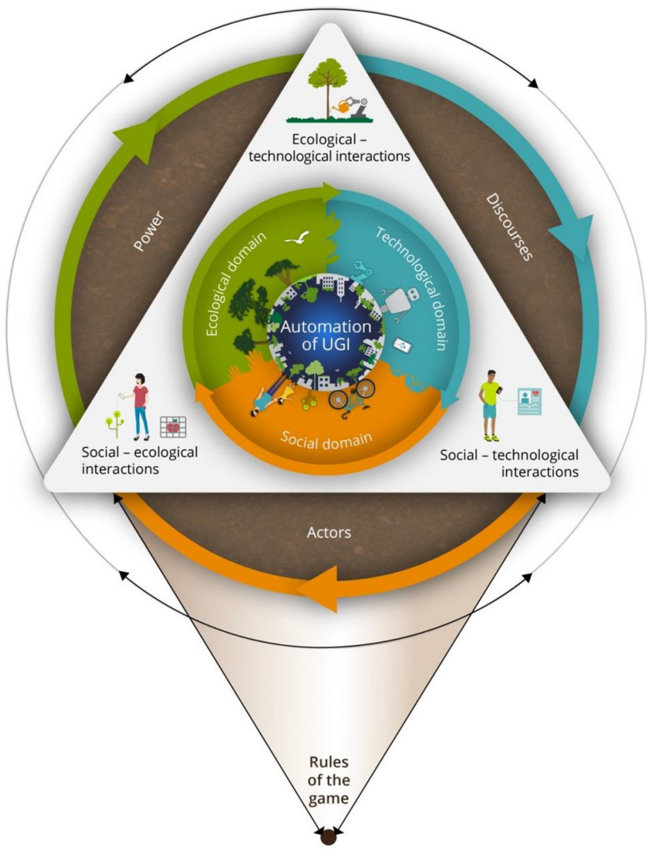

Fig. 1. The social, ecological, and technological couplings of the automation of UGI. The figure is adapted from Depietri and Mcphearson (2017).

Automated health monitoring may place too much responsibility on the individual and can mask important questions regarding the underlying social and institutional causes of health care crisis such as obesity, stress, and asthma (Kenner, 2016). Concerns have been raised regarding data sharing and privacy of health app users (Grundy, Wang, & Bero, 2016). Additionally, studies show that smartphone overuse can cause psychological duress referred to as "technostress" (Lee, Chang, Lin, & Cheng, 2014). Risks associated with the automation of citizen science touch on racial and socio-economic digital divides which favor citizens with agency and access to smart phones. Further, data sets from citizen science apps may not be accepted as authoritative scientific data (Burgess et al., 2017) which can undermine the co-creation and equity of UGI planning and policy.

4.3. Social-ecological interactions

The magnitude and direction of threat or opportunity in this context derives from how automation mediates human and social capital with natural, physical, and financial capital (Ellis, 2000), as elucidated in Case 1, virtual fencing of baboons and Case 5, automated tree stewardship. We see through the case of virtual fencing that increased wildlife conservation training with the local residents raises social capital through raised awareness of the need for baboon proofing on private homes and a reduction in human retaliation tactics such as shooting and traps.

Compared to physical fences, virtual fences allow for greater flexibility and may lead to improved urban conservation management. However, technical and logistical constraints limit its wider application (Brunberg, Bergslid, Bøe, & Sørheim, 2017; Jachowski, Slotow, & Millspaugh, 2014), while animal-mounted collars raise issues of animal welfare.

Case 5 (automated tree stewardship) has resulted in strong local attachment to and stewardship of existing and newly planted trees (Gulsrud et al., 2018). Since the strategy's implementation in 2012, Melbourne citizens have engaged in the planting of over 3000 trees annually. A diverse swath of citizens is now actively taking responsibility for the implementation of the strategy, contributing critical urban tree data, as well as in-person stewardship as citizen urban foresters. In this regard, a digital approach to UGI governance can be seen as integrating social-cultural and scientific knowledge to successfully promote and achieve higher-levels of urban biocultural diversity (Buizer, Elands, & Vierikko, 2016). Melbourne's collaborative and place-based UGI governance process diffuses power to many groups; however, citizens that fall outside of local interest groups, well-educated ranks, and the digitally-empowered, such as lower socio-economic populations, children, and the elderly, could be constrained from participation or a sense of ownership over the implementation process (Fincher, Pardy, & Shaw, 2016). Additionally, automated governance platforms have raised ethical concerns regarding increased surveillance (with app data harvesting) and the unknown consequences of automated governance technology, specifically in regard to the proprietary algorithms behind deep-machine learning (Zarsky, 2016). The proprietors of automated governance technology stand to gain enormous financial sums, an interest that could clash with those of citizen and public sector consumers (Taylor Buck & While, 2017).

5. Situating automation of UGI risks and opportunities in a wider social context

The previous sections focused on opportunities and risks of UGI automation associated with material interfaces (e.g., social-ecological interactions), linked to their application in a given setting. However, automation of UGI can impact on (and be impacted by) wider governance elements, including the rules of the game, actors, discourses, and power (Arts et al., 2006; Kitchin & Dodge, 2011).

So what do these wider trends mean for UGI governance? We propose that the impacts of automation on urban governance are not static but rather dynamic (Fig. 1). New types of actors, new discourses, can positively or negatively challenge the status quo in terms of how UGI management is automated, but these impacts are likely to be different across actors, as represented by the cone shape. Also, the impacts are likely to frequently change depending on the prevailing discourses of different actors engaged in the system, and their ability to influence or shift the rules of the game, as represented by the arrows across the cone and between the material and governance dimensions. These wider system elements are coupled to the specific context in which the automation is applied, and thus we refer to them as couplings. Below we present some specific implications for each coupling.

5.1. Ecological-technological coupling

The question of human oversight and citizen empowerment in the automated urban farming and robotic tree care cases reveals that interactions between the rules of the game (e.g., how regulations are adapted to respond to new urban farming innovations) and discourses (e.g., related to arguments of efficiency vs. job retention) will determine whose traditions, knowledges and cultures are represented in heavily automated urban landscapes. This coupling will be heavily dependent upon pre-existing institutional contexts and the governance of technology in urban ecosystem management (Smith & Stirling, 2010). The impact of heavily reduced human involvement in decision-making will be mediated by the extent to which the rules of the game account for the distribution of social welfare, health, and well-being (Galaz & Mouazen, 2017).

5.2. Social-technological coupling

Building on the ecological-technological coupling, the case comparison of automated health monitoring (Case 3) and youth-driven citizen science (Case 4) demonstrates the importance of considering for whose benefit automated systems are being deployed within UGI, and who has control of the data (Boyd & Crawford, 2012). Automated systems and apps could have an important role in supporting reflexive UGI governance processes to increase legitimacy and accountability of urban ecosystem development and management if they are co-created with a diverse and inclusive swath of citizens (Buizer et al., 2016). The case of citizen health monitoring highlights that employers and government officials might promote automated health monitoring in the name of fiscal responsibility and wellness while individual users might be burdened by the responsibility of self-care, personal data protection, and the 'technostress' of digital monitoring.

5.3. Social-ecological coupling

The management and stewardship of UGI will be determined by the aims, discourses, and rules of the game of sustainability (Smith & Stirling, 2010). The case comparisons of automated tree stewardship (Case 5) and virtual baboon fencing (Case 1) illustrate that automation can be delivered in ways that manage UGI for non-material values such as human and social capital while supporting important ecological functions (and ecological services) of the UGI. Managing UGI through automation for natural, physical, and financial capital could in-turn lead to the unintentional homogenization of landscapes and a decline in biodiversity. The automated virtual fencing case prioritizes sustainability for the food needs of local private gardeners at the expense of the territorial behavior of baboons.

As in the ecological-technological coupling, the rules of the game will mediate ethical questions regarding the technological propriety and transparency of digital management and stewardship tools. Digital UGI governance systems can cause issues of what Nguyen and Davidson (2017) aptly highlight as green 'techno-apartheid' whereby the benefits of UGI technological advancement are disproportionately captured by those already in power prompting an even larger gap in access to the benefits and sense of local ownership of urban ecosystems. Vertical farming (Case 2) can result in local people not directly benefiting from the food produced in the area; also such technologies do not allow for local involvement in food production, inhibiting gardening co-benefits such as social learning, sense of place, therapeutic restoration and sense of ownership of environmental problems (Barthel, Folke, & Colding, 2010). These trends point to concerns regarding fairness, transparency, and equity in automation governance, a finding recently highlighted by Zarsky (2016) in an evaluation of knowledge gaps and policy oversights in automated decision making.

6. Limitations and future directions

Computational technology is ubiquitous and in many cases hegemonic (Kitchin & Dodge, 2011) but there is little resistance to these technologies in UGI governance as of yet. However, the quick-fix context of technology means that there is a critical need to question what precisely is being made sustainable, for whom, and by which criteria. This is revealed in broader societal debates that highlight consternation and in many cases "rage against the machine" in terms of the unintended consequences of private data use, political exploitation of social media outlets, and overall corporate hegemony regarding automation.

In the synthesis of results we presented a conceptual overview of how a digital approach to UGI planning and management mediates the configuration and development of UGI grounded in a literature review and six case studies. We revealed such trends in a UGI context, particularly the dialectic between efficiency, human agency and empowerment. Risks and opportunities associated with UGI automation are not fixed but are dynamic properties of changing internal contexts (socio-ecological-technological interactions) and wider contexts comprised of tensions concerning power, actors, rules of the game and discourse (Fig. 1). Here we find the machine is not solely the automated entity but also the result of the existing technological regime system within which it is embedded. Hence, we question whether this rage is solely related to the outputs of the machine, but rather to the new and multiple spaces of engagement wrought by the machine.

This rage may look permanent, but can rupture as a result of citizen activism and legal recourse. We showed that the automation of UGI can have lock-on effects in terms of power allocation and resources, discourses, and actors that are difficult to change by government actors, at least in the short-term (Arts et al., 2015).

Nevertheless, the automation of UGI brings multiple opportunities for local actors to "rage against the status quo" by opening up new spaces of contestation and activism against hegemonic order (Kitchin & Dodge, 2011). We showed this in terms of the role of automation in providing voices to new actors in UGI governance, which could in-turn, inform new pathways of governance. Future research could consider the role of such automation in promoting multi-form partnerships between diverse actors and active citizen groups (i.e., mosaic governance) and in-turn positive outcomes for the management of UGI (Buijs et al., 2016). Additionally, there is an important need to assess how people-nature relationships co-evolve with machines as they take on more agency and more autonomy. Biocultural diversity (Elands, Wiersum, Buijs, & Vierikko, 2015), combined with the multi-level framework presented here, could be a fertile starting point to explore and evaluate integrated solutions that combine digital, social and nature-based solutions to support health and well-being in urban areas (European Commission, 2017).

Limitations to this conceptual approach touch on the lack of a spatially-grounded assessment in a particular place. Future research could focus on an investigation into the site-specific social, ecological, and technological couplings and their accompanying social and material processes at multiple scales. Investigations that uncover and interrogate co-benefits and costs associated with power, allocation, agency, and institutional arrangements in the automation of UGI may be particularly valuable. Specifically it is important to analyze and unpack automation processes in diverse typologies of UGI at multiple scales such as from urban balconies, to urban parks and community gardens to informal green spaces and highway verges. What kind of work is being performed by autonomous ecosystems? What new relational and contingent spaces are opened or closed through these systems? What are the potential implications moving forward?

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