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Smart Earth: A meta-review and implications for environmental governance

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ABSTRACT

Environmental governance has the potential to be significantly transformed by Smart Earth technologies, which deploy enhanced environmental monitoring via combinations of information and communication technologies (ICT), conventional monitoring technologies (e.g. remote sensing), and Internet of Things (IoT) applications (e.g. Environmental Sensor Networks (ESNs)). This paper presents a systematic meta-review of Smart Earth scholarship, focusing our analysis on the potential implications and pitfalls of Smart Earth technologies for environmental governance. We present a meta-review of academic research on Smart Earth, covering 3187 across the full range of academic disciplines from 1997 to 2017, ranging from ecological informatics to the digital humanities. We then offer a critical perspective on potential pathways for evolution in environmental governance frameworks, exploring five key Smart Earth issues relevant to environmental governance: data; real-time regulation; predictive management; open source; and citizen sensing. We conclude by offering suggestions for future research directions and trans-disciplinary conversations about environmental governance in a Smart Earth world.

1. Introduction

Over the past two decades, researchers and practitioners in earth sciences, ecology, and cognate disciplines have been creating innovations in environmental monitoring technologies that combine Information and Communication Technologies (ICT) with conventional monitoring technologies (e.g. remote sensing), and Environmental Sensor Networks (ESNs, which are spatially distributed monitoring networks containing high densities of sensors and actuators). These technologies, which we collectively label “Smart Earth,” have proliferated due to the rapid decrease in cost of cloud-based computing and innovations in Machine to Machine (M2M) infrastructure (Hogan et al., 2012; White, 2016), enabling unprecedented environmental management applications. Simply put, Smart Earth is the set of environmental applications of the Internet of Things, and is thus analogous to the widely discussed “Smart City,” (Marvin et al., 2015), but articulated across a much wider range of ecosystems and land use types.

Smart Earth technologies enable terabytes of environmental data to be derived from terrestrial, aquatic, and aerial sensors, satellites, and monitoring devices, relying on a rapidly diversifying set of sources—including “wearables” and biotelemetric technologies devised for humans, animals, and even insects. New cloud-based Web platforms have been created that enable the aggregation, analysis, and real-time display of these unprecedented streams of environmental data. Scientists are also applying innovations in AI, Big Data analytics, machine learning, 3D object-recognition algorithms, and genetic learning to the study and administration of ecological processes (Koomey et al., 2013; Gabrys, 2016; Goodchild, 2007; Kitchin, 2014; Gale et al., 2017; Pettorelli et al., 2014; Schwab, 2017; Zyl et al., 2009). Collectively, these developments have dramatically increased scientists’ ability to assess spatiotemporal changes in abiotic conditions as well as biotic communities.

We contend that the volume, integration, accessibility, and timeliness of the data provided by Smart Earth technologies potentially creates the conditions for significant changes in environmental governance. To date, the majority of research on this topic has focused on the potential implications for conservation and waste reduction, pollution mitigation, mapping environmental degradation, geosecurity, and disaster management (Goodchild and Glennon, 2010; Resch et al., 2014; Koomey et al., 2013). However, although a few scholars have engaged with questions of the implications of these technologies for environmental governance (e.g. Gabrys, 2016), this issue remains relatively under-studied from a multi-disciplinary perspective. This paper seeks to address this gap.

Our paper begins from the premise that Smart Earth technologies have the potential to disrupt existing modes of environmental governance. Here, environmental governance is defined from an analytical (rather than normative) perspective as the set of social actors and

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institutions (including laws, rules, norms, customs), as well as data-gathering and decision-making processes, engaged in environmental decision-making (Bridge and Perreault, 2009; Ostrom, 1990). Our definition is broadly aligned with social scientists engaged in the study of environmental governance at a global scale (e.g. the Earth System Governance Project), notably those who study the institutional and epistemological realignments of environmental governance globally (e.g. Biermann et al., 2010, 2012). Our analysis of potential pathways for innovation in environmental governance coupled with Smart Earth technologies is related to and inflected by, but distinct from, governance trends such as the partial redistribution of decision-making power from state to non-state actors (e.g. the emergence of non-state market-driven governance systems), and the rescaling of governance above and below the nation-state (Biermann et al., 2012; Cashore, 2002; Cohen and McCarthy, 2015; Reed and Bruyneel, 2010).

The purpose of this meta-review is to provide a synthesis of key issues and critiques that Smart Earth poses for environmental governance. Smart Earth enables a series of shifts: the time-space compression of data availability and decision-making (which in turn enables automated real-time regulation and new prediction capabilities); the multiplication of modalities and agencies of environmental sensing; the proliferation of new environmental governance actors; and, potentially, a much higher degree of transparency in data collection, accessibility, and integration. Taken together, these innovations create the conditions for potentially significant transformations in environmental governance.

Consider, as an example, Sustainability Standards Organisations (SSOs). New forms of access to real-time, continuous information on environmental data from "virtual" monitoring platforms are challenging the "static, limited, and closed "analog" model of auditing conventionally employed by [SSOs]" (Gale et al., 2017). In the past, SSO audits were conducted through brief, intermittent field visits by small teams of auditors and experts. Smart Earth technology creates the potential for continuous monitoring and assessment of the validity of sustainability claims. This in turn enables the emergence of private regulatory bodies and real-time auditing processes which will drive changes in SSOs (Auld and Gulbrandsen, 2010; Carse and Lewis, 2017). The SSO example illustrates the co-evolution of technology and governance occurring across different environmental domains and scientific disciplines, including established fields such as landscape ecology and geography, as well as emergent sub-fields such as environmental digital humanities, animal biotelemetry, and citizen sensing.

Our paper presents a systematic meta-review of this literature. Our intention in conducting this review is to identify the key issues that Smart Earth poses for environmental governance. To conduct this meta-review, as detailed in Section 2, we surveyed the scholarly literature (1997–2017) across the full range of academic disciplines to create a database of 3187 articles (discussed in Section 3). In Section 4, we present key issues and critiques relevant to environmental governance debates, including: data (the opportunities and challenges of using big data to provide temporally and spatially comprehensive coverage for monitoring, in contrast to intermittent and low-density monitoring); real-time regulation (including real-time and potentially automated decision-making through the use of mobile platforms to communicate to field-based actors and receptors, such as ship captains, farmers, fishers, and hunters); enhanced predictability, particularly in situations where data was previously unavailable; the technical and ethical implications of open data; and the evolution of citizen engagement through new modalities such as citizen sensing, which incorporate new variables (such as noise and sound) that extend our ability to "sense" the environment (Helmreich, 2015). Section 5 concludes by offering suggestions for future research directions regarding environmental governance in a Smart Earth world.

2. Methods

Our analysis presents the results of a meta-review of the academic literature on Smart Earth. We conducted a manual search of 17 journals spanning a range of disciplines including computer science, environmental studies, ecology, eco-informatics, and social studies of science. Our manual search included the following journals: Ambio, Annual Review in Environmental Resources, Ecological Informatics, Environmental Humanities, Environment and Planning A, Environment and Planning D, Journal of Applied Ecology, Big Data and Society, Annals of the American Association of Geographers, Global Environmental Change, Global Environmental Politics, International Journal of Digital Earth, PNAS, Nature, Science, Social Studies of Science, Trends in Ecology and Evolution.

Through this review, we identified the keywords most frequently used with respect to Smart Earth, as well as commonly-used terms related to earth processes relevant to Smart Earth topics: remote sensing, eco-informatics (and ecological informatics), Big Data, biomonitoring, citizen sensing, cloud computing, data visualization, fiber optic, Internet of Things, drones, citizen science, fourth industrial revolution, Digital Earth, biomonitoring, and Program Earth. Keywords relevant to earth processes related to Smart Earth-related topics: ecosystem services, environment, ecology, Anthropocene, planet, habitat, species, biodiversity, animal migration, geology, geomorphology, conservation, ecosystem, species distribution, migration, and climate. We then conducted a search using these keywords across the full range of disciplines in the natural sciences, social sciences, and humanities, on Web of Science and Google Scholar. Using paired combinations of keywords, we generated 176 discrete paired search terms. With each paired search, we identified the top 100 most cited papers, inclusive of the period 1997–2017, the period which best captures the onset phase of Smart Earth research. This strategy identified the most highly-cited papers (7892 papers in total). Each paper's abstract was reviewed to determine whether or not the paper focused on Smart Earth issues, resulting in a database of 3187 articles, the citations from which were used to generate a content cloud (Fig. 1). These articles span the natural and social sciences, and humanities, and include such disciplines as ecology, environmental humanities, geography, geomorphology, and marine biology; and such topics as animal migration studies, eco-informatics, pollution monitoring, remote sensing, and science and technology studies (STS).

3. Smart earth: overview

This section provides an overview of the Smart Earth literature, which is characterized by a focus on Smart Earth techniques and technologies. Twenty years ago, many of the technologies that are now

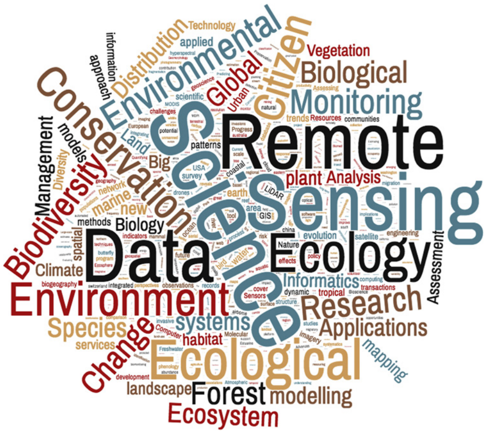

Fig. 1. Smart Earth – Content Cloud.

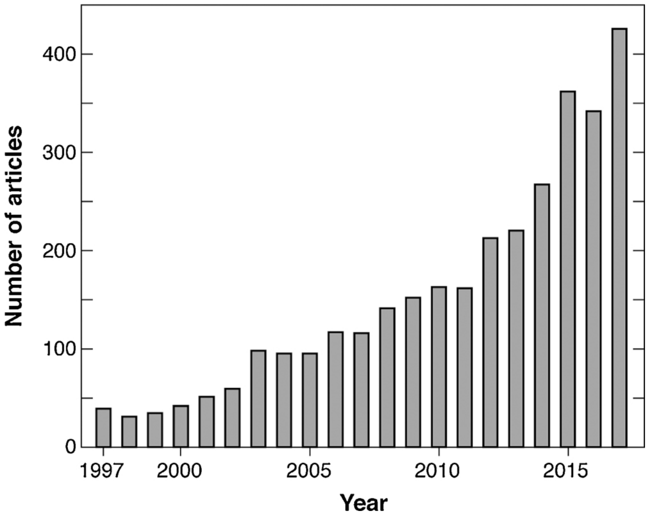

Fig. 2. Smart Earth publications (1997–2017).

aggregated under Smart Earth were nascent or nonexistent. Conversations had yet to form – or at least, become formalized – across many of the scientific disciplines that deploy and debate these technologies. Over the past two decades, new interdisciplinary journals have emerged, including *Ecological Informatics* (founded in 2006), the *International Journal of Digital Earth* (2008), and *Environmental Humanities* (2012). New disciplines have formed (e.g. Digital Environmental Humanities), emblematic research groups have been founded (e.g. MediaLab at Sciences Po, founded by leading social theorist Bruno Latour), and there have been notable transformations in the character of sub-disciplinary fields: for example, Geo-Information Sciences has grown out of Geographic Information Systems.

As Fig. 2 indicates, publications on Smart Earth have rapidly increased in number. Our bibliometric analysis indicates that use of terms like "Big Data" has increased across a range of disciplines. Although we restricted our searches to peer-reviewed, English-language publications, our meta-review likewise illustrates a diversity of disciplines and disciplinary approaches in research on Smart Earth: Agriculture, Anthropology, Applied Physics, Astronomy, Astrophysics, Atmospheric Sciences, Biochemistry, Biology, Biotechnology, Business, Cell Biology, Communication, Computer Science, Conservation, Ecology, Economics, Energy and Fuels, Engineering, Entomology, Environmental Sciences, Environmental Studies, Evolutionary Biology, Fisheries, Forestry, Geography, Geology, Limnology, Marine Biology, Mechanics, Microbiology, Nuclear Chemistry, Oceanography, Ornithology, Plant Physiology, Plant Sciences, Remote Sensing, Robotics, Soil Science, Spectroscopy, Toxicology, Water Resources, and Zoology.

Entirely new sub-disciplines – such as the Environmental Humanities, a field designed to explore conjunctions across environmental history, philosophy, human geography, and political ecology – are now regularly engaging Big Data questions (e.g. Gabrys et al., 2016). Remote sensing continues to enjoy a great prominence in Smart Earth publications, but is by no means the only technical application being explored in Smart Earth. Companies like Microsoft and Google are now investing significant amounts ($50 Million from Microsoft alone) to develop AI-supported "Earth algorithms" (Joppa, 2017). Other initiatives include Nokia's "Sensor Planet," IBM's "A Smarter Planet," HP Labs' "Central Nervous System for the Earth" (CeNSE), NASA's "Earth Observing System Data and Information System" (EOSDIS), and Cisco/NASA's collaborative "Planetary Skin Institute," together with a rapidly proliferating ecosystem of apps (Jepson and Ladle, 2015).

Many of these initiatives focus on the interface between sensors and internet-based communications technologies which, combined with cloud-based data storage, enable unprecedented real-time tracking and visualization (Gale et al., 2017). Smart Earth initiatives also frequently combine well-established approaches – such as remote sensing and long-term ecological monitoring – with newer technologies (e.g. animal biotelemetry, bacteria-based biosensors) and modalities of data

Table 1
Examples of Smart Earth technologies.

Type	Example	Description
Wearables	Flow	Flow is a smart, wearable air pollution tracker using sensors to monitor the user's real-time exposure to air pollution and an integrated app to help users find cleaner air (Flow, 2017).
Animal Biotelemetry	Save the Elephants: Geo-fencing	Geo-fencing, a virtual fence programmed with GPS positions, has been integrated into elephant tracking collars to get real-time information of their location, allowing for immediate action if an elephant moves out of the reserve into areas more susceptible to poaching (Save the Elephants, 2017).
Plant Biotelemetry (Cyberplants)	PLEASED	The project Plants Employed As Sensing Devices (PLEASED) embeds EEG sensors into plants to measure environmental parameters, which can be used to monitor fires and avalanches (PLEASED, 2017; Manzella et al., 2013).
Insect Biotelemetry	Bees with Backpacks	By attaching small RFID 'backpack' sensors to over 5000 honey bees, the data collected on bees' location and movement will provide insight into the decline of Australian regional bee populations (Landau, 2016).
Mobile apps	giveO2	The app giveO2 automatically tracks the user's means of transportation, identifies their carbon footprint using GPS, and gives users the opportunity to purchase carbon credits to offset their carbon output (GiveO2, 2018).
Fixed sensors	Instant Detect	Instant Detect has been successfully deployed in Kenya to tackle poaching thanks to its network of multiple fixed camera traps using a central satellite node to instantly send photographs and data (Zoological Society of London, 2018).
Mobile sensors	Argo	Argo consists of 3800 free-drifting ocean floats with mobile sensors attached that transmit data on salinity and temperature from the upper 2000 meters of the ocean to satellites (Argo, 2017).
Sensor Web	Ocean Observatories Initiative (OOI)	Dubbed the 'Fitbit for the oceans' (Paul, 2015), OOI's cyber-infrastructure is exploring the little-known parts of Earth's oceans with sensors and autonomous drones collecting over 200 types of data (Ocean Observatories Initiative, 2016).
Remote sensing	GasFinder3	GasFinder3 utilizes laser-based remote sensing to continuously monitor gas concentrations in the path of the laser, and has been successfully applied around oil and gas sites in the Arctic region (Boreal Laser Inc, nd; LOOKNorth, 2012).
Virtual reality	Conservation in Virtual Reality	Conservation International's 360-degree virtual reality films immerse viewers in environmental conservation efforts around the globe, including the Amazon rainforest and Indonesian reefs (Conservation International, 2017).
Artificial Intelligence (AI)	Green Horizon	Green Horizon's cognitive computing systems use machine learning and real-time air quality data to analyze and create visual maps displaying the source and dispersion of pollutants across Beijing (IBM, 2018).

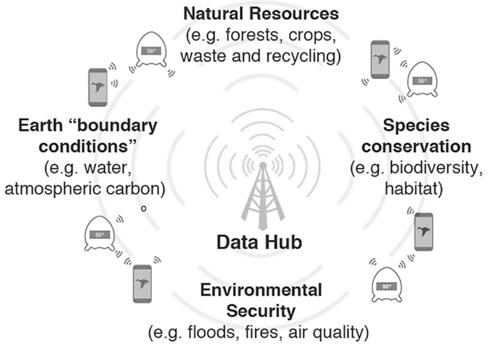

Fig. 3. Smart Earth – Data Hub.

collection (such as drones, Google Earth, and citizen sensing) (Table 1). The most frequent targets of these applications are: natural resources (such as forests); species prioritized for conservation (such as marine mammals); earth “boundary conditions” and “ecosystem services” (such as freshwater, atmospheric carbon); and environmental security (e.g. natural disasters such as floods and fires) (Fig. 3).

A paradigmatic example of Smart Earth technologies is EarthNC’s (2016) SharkNet (www.sharknet.com/), which displays the near real-time locations of great white sharks and marine mammals, gathering data from a network of mobile robots and moored listening stations connected to sensors carried by marine wildlife. Like many marine animal tracking efforts, SharkNet emerged from longstanding collaboration among scientists interested in monitoring animals across large spatial ranges. Related “citizen sensing” projects have geotagged fish, such as important commercial species like Pacific salmon, whose movements can likewise be detected by networks of underwater cameras (Matabos et al., 2017).

Although the focus of Smart Earth has tended to be on terrestrial processes, ocean environments have also been the subject of innovation (ONC, 2014; IBM, 2014; Favali et al., 2015). Across a range of ecosystems and disciplines, scientists and engineers have created new devices to assess changing oceanographic conditions, including an automated network christened “FitBit for the Oceans” (Ocean Observatory Initiative, 2016). The network incorporates cable and sensor technologies to measure geological, physical, chemical and biological variables in the ocean and seafloor and produces over 200 different kinds of data. These marine developments are emblematic of the ways in which Smart Earth technologies enable comprehensive data acquisition infrastructures to monitor environmental conditions, emergent risks, and geo-hazards (see: ONC, 2014; Helmreich, 2015; Lehman, 2016; Lindenmayer et al., 2017).

Another salient finding of our review is the variability of scales at which Smart Earth is being defined and measured. Scale is critical in assessing Smart Earth because of the spatial variability of the ecological processes involved in environmental governance. For instance, the designers of BeachObserver propose that coastal communities “self-monitor” locally-occurring marine debris, whereas projects like Argos aim for systemic reviews of marine-ecological change occurring at the planetary scale (Benson, 2015). A single review is probably unable to capture all the scalar variability in Smart Earth, although certain projects (e.g. BirdTracker) are able to straddle multiple scales. However, the challenge of integrating technologies operating at multiple and distinct scales is obvious and will be discussed further below.

4. Environmental governance in a smart earth world: issues and critiques

This section of the paper offers insights into the key implications of Smart Earth for environmental governance. We explore key issues and critiques stemming from our meta-review, organized by five themes: data; “real-time” analysis and regulation; the changing nature of prediction; the meaning and extent of “open data”; and the role of non-scientists, notably “citizen sensors.”

4.1. Data

Smart Earth technologies require new multi-scalar data architectures which can provide computing resources and/or services such as data replication and storage (Coleman, 2010; Kitchin and McArdle, 2016; Li and Chen, 2017). The exponential growth in data generated by Smart Earth technologies is illustrated by the collaborative work of IBM and research scientists on Lake George in the north-eastern United States (Coldsnow et al., 2017; McGuinness et al., 2014). The collaboration between biologists, environmental scientists, engineers, physicists, computer scientists, and meteorologists implemented an unprecedented array of sensors to produce 468 million depth measurements (compared with 564 data points in previous models). As this example illustrates, Smart Earth reverses a prior constraint: in the future, it is the abundance (rather than scarcity) of data that will be a defining challenge for effective environmental governance.

In response, many scientists and innovators are focusing on developing automated decision-making systems. The growing embrace of automated management techniques (including water and pesticide application, and crop rotation) in the agricultural sector is a good example of these trends (Zhang and Pierce, 2013). However, multiplying real-time data streams and interoperable technologies does not necessarily engender more efficient or transparent modes of environmental governance. Angwin (2013), for example, cites a coder behind the National Security Agency’s (NSA) analytics who speculates that his agencies’ data collection efforts may actually be hindering its surveillance efforts; the NSA is simply awash in too much data.

Galaz and Mouazen (2017) point to a related paradox: the most powerful algorithms underlying automated decision-making systems are likely to be of limited accessibility or transparency—raising the risk of replication of biases in decision-making. As many scholars have pointed out, AI and machine-learning driven approaches often contain implicit bias; incomplete datasets and flawed algorithms can prove counterproductive and ecologically damaging (Caliskan et al., 2017; Galaz and Mouazen, 2017). Moreover, algorithms do not reconcile value-laden tensions between competing uses and ecosystem services (e.g. economic versus spiritual values) leaving the question of arbitration incomplete. Perhaps counter-intuitively, this creates a need for new forms of human supervision as the automation of decision-making intensifies (Galaz and Mouazen, 2017, p. 629).

A related issue that threatens to inhibit the uptake of Smart Earth data in environmental governance projects is the lack of data standards across different institutional cultures (Michener, 2015). Our meta-review revealed persistent appeals for cross-disciplinary collaboration on data standards and data sharing (e.g. Frew and Dozier, 2012; Hampton et al., 2013; Michener, 2015). It is thus surprising to note that “silo-ing” persists across academic uptakes of Smart Earth. This can be partially attributed to the long-standing challenges of combining ecological data sets. Pre-ICT approaches were characterized by a diversity of standards; for example, one set of standards applied to the longer-term data gathered by professional scientists (often for the purposes of testing single hypotheses), while another set of standards often applied to shorter-term data collected by professional environmental consultants in response to specific ecological threats (such as pollution incidents), and distinct (or no) standards were applied to data collected by citizen scientists (such as fish and wildlife harvest data) which was housed separately and rarely accessed or used by scientists or governments (Goodchild, 2007). The challenge of combining and communicating data gathered through disparate data collection efforts remains unresolved, although significant efforts have been made to address this issue by a variety of organizations, including NASA’s Socioeconomic Data and Applications Center (SEDAC, a Data Center in NASA's Earth

Observing System Data and Information System (EOSDIS)) and the National Ecological Observatory Network.

This data-sharing challenge may nevertheless be largely resolved in the near-term future. "Big ecology" policies, combined with diminished costs for information technologies and new cloud-based data archiving tools and repositories, have proliferated in recent years (Michener, 2015), supported by an increasing number of eco-informatics scientists, and also by the work of organisations such as the Ecological Society of America's Committee on the Future of Long-term Ecological Data (FLED) (Michener et al., 1997; Porter, 2010). Scholars of ecological informatics predict that the new generation of data sharing networks will grow exponentially faster than its predecessors (Michener, 2015; Porter, 2010; Reichman et al., 2011; Zimmerman, 2008). For example: after several decades of operation, the US Long Term Ecological Research Network (LTER) had 6000 shared datasets (Porter, 2010); in contrast, by mid-2017, after less than a decade of operation, DataONE exceeded 1 million data objects. This growth has been facilitated by the expansion of networking capacities among researchers, along with corresponding changes in the cyberinfrastructure landscape. Important data science innovations—including data and metadata standards, persistent identifiers, and search/discovery tools—have enabled more widespread data-sharing than in the past (Michener, 2015). (A detailed exploration of these aspects of ecological informatics is beyond the scope of this paper but for a representationally-focused critique see: Demos, 2017).

In summary, much of the Smart Earth literature focuses on addressing data gaps, the need for more collaborative data sharing, and issues relating to data quality. The underlying assumption is that more comprehensive and higher quality data will lead to more effective environmental governance. As a wealth of literature in science and technology studies shows, however, this assumption is problematic (c.f. Jasanoff, 2003; Gabrys, 2016). The political commitments associated with measurement-related decisions—in particular, the question of who selects variables to measure and for whom they are selected—are rarely discussed. Because data gaps are likely to become more acute in a Smart Earth world, the problem that "what is measured, matters" or "what is counted, counts" (and by extension, what is not counted does not count) is likely to intensify. These critiques are central to the question of whether Smart Earth will truly enhance and not simply "update" environmental governance.

4.2. *Real-time regulation*

The concept of "real-time" – e.g. the increasingly instantaneous "actual" time elapsed in the performance of a computation – is central to Smart Earth governance (De Longueville et al., 2010). Interest in real-time regulation can be traced to the managerial discourses shaping urban policy in the late 1990s (for reviews see: Komninos, 2002; Gabrys, 2014), which focused on real-time pricing in "Smart Grids" and "Smart" water distribution systems (Momoh, 2012; Kratz et al., 2006). In the last decade, a rapid decline in the cost of monitoring technologies (driven by innovation in computing and communications) has increased the capacity to conduct real-time assessment of environmental changes (Koomey et al., 2013). Managers are evaluating the success of real-time location information via software applications on location-aware devices, such as cellphones (e.g. Ratti et al., 2006), laptops (Goodchild and Glennon, 2010), acoustic sensors (Farina and Gage, 2017), and apps (Zickuhr, 2013). Formative efforts to explore the implementation of "real-time speed advisory signs" in transportation systems (Haque et al., 2013, p.25), are now common in larger environmental governance contexts, such as marine governance, where ship rerouting efforts proceed in response to wildlife detections in a number of contexts (the Enhancing Cetacean Habitat and Observation, or ECHO, project noted in Ritts, 2017); and pipeline logistics, where flows can be rerouted into different distribution terminals across vast inter-regional networks (e.g. Cowen, 2014).

A paradigmatic example here is the work of Conserve.io, an organisation that assists conservation groups with leveraging mobile, cloud-based and big data technologies through data collection at scale (involving both crowdsourced data from humans and passive environmental sensors). The mobile applications ("apps") produced by Conserve.io (2015) use visual analytics to enhance situational awareness and real-time responses to environmental changes. Whale Alert (2012) (http://www.whalealert.org/) gathers marine mammal observations (both volunteered and professionally-sourced) in marine shipping zones, and uses the data to alert ship captains of vessel proximity to high density whale zones in real-time, with the goal of providing real-time information to reduce whale strikes.

Whereas management and critical policy literatures focus on real-time resource distribution concerns – e.g. coordinating flows of energy, bodies, and commodities – ecologists and biologists have been more engaged with novel possibilities for species "tracking" (Benson, 2012; Gabrys, 2016). Thanks to new advances, tracking efforts can now distill real-time patterns. New technologies, such as conservation drones (Sandbrook, 2015), augmented virtual environments (Jian et al., 2017), and conservation apps (Jepson and Ladle, 2015) are being evaluated as adaptive solutions to monitoring and law enforcement problems. It is increasingly common for large scale observatories – whether located underwater (e.g. VENUS) or in the sky (ARGOS) – to host multiple sensor arrays for multiple research communities (Starosielski, 2015; Benson, 2015).

The challenge (and opportunity) posed by real-time data streams is one of the most salient issues for environmental governance in a Smart Earth world. Real-time data streams and real-time analysis make the idea of "real-time" regulation possible: e.g. the capacity to rapidly shift resources and monitoring capacities in response to unforeseen developments. For example, Little et al. (2015) survey real-time spatial management approaches to reduce fisheries bycatch and discards. Kumar et al. (2015) explore the rise of low-cost sensing for managing urban air pollution. The developments they capture likewise sound a note of caution. Real-time regulation poses significant administrative challenges, insofar as organizing simultaneous temporal attributes (or tracking efforts), including time of acquisition, integration/dwell time, sampling interval, and aggregation time span, can easily overwhelm computing power or lead to insufficient data (Frew and Dozier, 2012; Barnes et al., 2013; Benson, 2015). It is likewise impossible to guarantee that ecological wellbeing will form the basis of real-time responses, which may in fact embolden more tactical political decision-making favoring certain actors. This has spurred cross-disciplinary demands for new protocols, so that meaningful results can be obtained and acted upon (e.g. Koomey et al., 2013; Snyder et al., 2013).

A second, related issue is the logistical challenge of sharing insights across spatially and institutionally distributed research communities (Hochachka et al., 2012). Fox and Hendler (2011) observe a growing mismatch between the resource cost of creating scientific visualizations, and the more rapidly decreasing costs of data generation (per unit of data generated). Because digital devices are functional only to the extent of their integration into superannuating real-time networks (Wilson, 2014), the problem of "dark data" – i.e. data rendered invisible (and hence unusable) in Smart Earth practices – looms (Hampton et al., 2013; see also: Roche et al., 2015). Real-time regulation presupposes the constant availability of power-sources for its effective operation: an expectation that more and more coastal communities are routinely disabused of (Parenti, 2012). The sudden absence of power demanded by real-time coordination systems could multiply distributional challenges in the face of a brownout or similar disruption. Cubitt's (2017) claim that insufficient electricity, not oil, is the leading threat to coordinations of global governance takes on added salience in Smart Earth. More research is needed to build on important efforts, such as Graham's (2010) study of infrastructural failure, to investigate the challenge posed by the multiplication effects of small energy stoppages (even at the orders of seconds and nano-seconds) to real-time environmental governance.

4.3. Prediction

Many papers discussing Smart Earth highlight the benefits of predicting conditions for sustainable development and resource use (Snyder et al., 2013; Schwab, 2017). In distinction from previous approaches to predictability, ecological changes are increasingly conceived as predictable and "programmable" (Frew and Dozier, 2012; Gabrys, 2016; Leszczynski, 2016; Murai, 2010). This innovative emphasis on programmability as an inherent—and in some formulations paramount—characteristic of predictability builds on developments in "adaptive monitoring" and "adaptive management" (e.g. Lindenmayer and Liekns, 2010), as well as "anticipatory governance," which Guston (2011, p.1) defines as "a broad-based capacity extended through society that can act on a variety of inputs to manage emerging knowledge-based technologies while such management is still possible" (see also: Carruth and Marzec, 2014). For example, many publications provide examples of enhancements to predictive capacities enabled by new web platforms (e.g. OakMapper, WhaleAlert; Global Forest Watch), from which managers and scientists alike can source data inputs for environmental niche models, which are able to predict risks, disturbances and terrestrial transformations (Kluza et al., 2007; Clark et al., 2009).

Smart Earth also creates innovative possibilities for predictability for an expanded set of environmental variables. For example, the literature has many examples of novel prediction capabilities across environmental phenomena which were previously characterized by limited predictability – with seasonal whale migrations, and the sonification of advancing "P-Waves" being two prominent examples (e.g. Walsh and Mena, 2013; Pötzsch, 2015; Gale et al., 2017; ONC, 2014). Prediction has also garnered considerable attention in the remote sensing community (Khatami et al., 2016), where new measurement techniques and modeling and visualization capacities are being used to describe and predict local weather patterns in the context of climate change (Mairota et al., 2015), species diversity estimates (Rocchini et al., 2015), lake monitoring (Dörnhöfer and Oppelt, 2016), and management priorities (Pettorelli et al., 2014). Again, innovation is key: Fractal measures, Fourier decomposition, wavelet measures, and spatial autocorrelation (Cushman et al., 2010) represent powerful advances over discrete patch-matrix-corridor models, and serve to generate continuous predictive evaluations of landscape patterns, which can then feed into long-term projections and detailed anticipations of future ecological forms (Mairota et al., 2015). There are a range of studies centered on the prediction, with increasingly high degrees of accuracy, of changing forest structure and aboveground biomass (Zald et al., 2016); food web structure (Woodward et al., 2013); and animal migration (Panzacchi et al., 2016).

Despite their potential, the actual success rate of predictive efforts has been questioned. Hummel et al. (2013) note that future trends in water consumption cannot simply be modeled through population inputs and the provision of known-aquifers. Such determinations will have to contend with "unexpected developments" (p. 122) in price structures and consumption patterns, among other variables. Hochachka et al. (2012, p. 132) regard as a "persistent general challenge" the fact that "relationships between fine-scale environmental predictors and the observed responses of species tend to vary across large spatial and temporal extents." Predictive capacities are necessarily limited by the present-day assumptions of their programmers, and they are often unable to internalize challenges that arise outside their framing contexts (see: Amoore, 2013; Leszczynski, 2016). Finally, as Jasanoff (2003) notes, technologies of predictive analysis have historically tended to pre-empt political discussion on the basis of scientific claims to objectivity. The challenge of flexibility alongside predictive capacity can be expected to loom as a major tension in Smart Earth governance moving forward.

In short, Smart Earth enables new modes of prediction which create new possibilities for environmental governance. Adaptation and anticipation have become more central to environmental governance in the increasingly predicted (if not necessarily more predictable) "time-space" of a Smart Earth world. These developments align with current debates over the implications of what Mahony (2014) calls the "predictive state" (Guston, 2011; Gabrys, 2015, 2016; Pötzsch, 2015) and associated forms of geographical intelligence (Crampton et al., 2013; Wood, 2013; Thatcher, 2014). Carruth and Marzec (2014) join others in focusing these concerns around ethical issues of privacy, freedom, and security (e.g. Wood, 2013; DeLoughrey, 2014). Cubitt's (2017, p.159) remark that "databases predict the predictable" is a reminder that certain ecological forms and processes may be excluded under automated tracking systems.

4.4. Open source

A Smart Earth world abounds in rapidly circulating, often messy and insufficiently inventoried "open source" data (Gunningham and Holley, 2016; EPA, 2013; Mairota et al., 2015; Rocchini et al., 2017). In the ecological sciences, there is now a pervasive conviction that biodiversity conservation will be augmented by the provision of open-access data (Morris and White, 2013; Turner et al., 2015). Projects like eBird tout the value of sharing small, localized citizen-science based observations which, when aggregated, propose broader understandings of ecological phenomena (e.g. Dickinson and Bonney, 2012; EPA, 2013; Snyder et al., 2013). The "Air Quality Egg" project, an EU-supported effort to collaboratively devise a "smart" air quality sensor network, is being proclaimed as a best practice example of bottom-up environmental governance (Zandbergen, 2017). In contrast, "Open source" is defined by other scholars as a means to facilitate customization in environmental governance (e.g. Bradley and Pullar, 2015; Gale et al., 2017), ensuring the local determination of environmental decision-making at a time of planetary-scale organization. At its most utopian, open source proposes that "ubiquitously available" data can serve as both a key feature of environmental governance and an "essential component of democracy" (Mooney and Corcoran, 2014, p.534).

Efforts to survey the dizzying array of open source archives currently engaged within governments, research projects and NGOs have resulted in several detailed reviews (Roche et al., 2015; Gale et al., 2017; Welle Donker and van Loenen, 2017). Michener (2015) examines how "Big Data" informational policies have historically encouraged the present deluge of open source data – noting in particular the foundational significance of Long-Term Research Networks (LTRNs), Ecological Observatory Networks (EONs), and Coordinated Distributed Experiments and Observations Networks (CDEOs). Bastin et al. (2013) survey the range of open-source software and standards (e.g. PostGIS, OpenLayers, Web Map Services, Web Feature Services and GeoServer) that support new assessments of land-cover change. Despite the fact the scientists have long used decentralized groups of non-professionals to gather ecological information (Connors et al., 2012), many observers note that recent "success stories" remain without truly democratic cultures of "collaboration" (Brondizio et al., 2016), and "sharing" (Faniel and Zimmerman, 2011). Collaboration and data sharing as such remain considerably removed from the actual opportunities enabled by Smart Earth (Ellison, 2010; Reichman et al., 2011; Hampton et al., 2013; Volk et al., 2014). Reviews of marine-based sciences have made similar observations (e.g. Costello, 2009; Starosielski, 2015), as have recent publications within environmental and digital humanities (e.g. Borgman, 2009; Cubitt, 2017). A commonly raised concern is the absence of proper institutional support for collaborative data sharing (e.g. Michener and Jones, 2012; Roche et al., 2015; Specht et al., 2015), which in certain cases might translate into prescriptions for greater incentives to share (Hampton et al., 2013); and the embrace of novel administrative frameworks (e.g. Verburg et al., 2016). Humanities scholars have been particularly keen to critique "crowdsourcing" as a source of ecological knowledge that tends to reinforce the expert hierarchies it proposes to disable (e.g. Gabrys, 2015; Swanstrom, 2016; Pearson et al., 2016).

For many observers, open source data leads inexorably to the problem of data standards, an issue with far-reaching consequence to Smart Earth environmental governance. Roche et al., (2015) surveyed 100 datasets associated with studies in journals that commonly publish ecological and evolutionary research, finding that 56% of the articles were linked to incompletely archived datasets. Calls for improved metadata have become increasingly common in ecology and biodiversity science (e.g. Frew and Dozier, 2012; Specht et al., 2015; O'Brien et al., 2016). "Good news narratives," showcasing the purported benefits of Smart Earth technologies (Arts et al., 2015, p.661), often obscure questions of quality controls and who will set them. The question of just what constitutes "good enough data" (Gabrys et al., 2016) prefigures a growing politics of "open source" legitimacy in Smart Earth environmental governance. At a time when increasing amounts of data freely circulate, and many scientists advocate for the continued diversification of research models (e.g. Verburg et al., 2016), the integration of data from multiple sensors poses institutional challenges and social tensions (e.g. Snyder et al., 2013). Moreover, what role do different data sources play in the actual conduct of environmental governance? In the Digital Fishers (2018) project (dmas.uvic.ca/DigitalFishers), for example, citizen scientists are solicited for their ability to identify species types on freely-available video data streaming from underwater cabled observatories. But the resulting citizen science is more proper characterized as a kind of volunteered filtering that allows scientists-experts to better identify the videos worth reviewing themselves (Matabos et al., 2017). The actual provision of open source data articulates a fundamental ambiguity of the Smart Earth governance regime: are data flows simply feeding into the predetermined interests of large multinationals (Crampton et al., 2014; Wood, 2013), or are they truly sites of continual "bottom up" modifications and "hacker-led" transformations (Hemmi and Graham, 2014)?

4.5. *Citizen science/sensing*

Smart Earth engages a broad set of actors. Researchers in disciplines as diverse as ecology, oceanography, geomorphology, political science, and sociology are now applying the Smart Earth concept. Smart Earth also engages non-professional researchers. For example, through "Volunteered Geographic Information," or VGI, community groups and NGOs are developing spatially-distributed, high-quality research outputs (Goodchild and Glennon, 2010). Some scholars have also explored the potential contribution of Artificial Intelligence (AI) to ecology, natural resource management, and wildlife conservation (Rykiel, 1989; Castelli et al., 2015; Millie et al., 2014), thereby invoking parallels with related transitions from "Web 2.0″ to "Web 3.0″, in which environmental governance is enabled by a connective intelligence that articulates sensors, humans, non-humans, data, and decision-making applications.

This transition will be intensified by Smart Earth's multiplication of sensing practices. Recent innovations create the potential for universal biotic sensors, in which every organism potentially performs as a sensor to be integrated into an array of data hubs and initiatives (such as the Sensor Web, Participatory Geoweb initiatives, and Google Earth) (Goodchild, 2007; Huang and Liang, 2014; Sieber, 2006). Smart Earth research agendas deploy many technologies which make use of the filtering and transducing capacities of bio-sensors (e.g. eyes, ears, skin etc.), as well as providing actionable data to users (e.g. via geospatial visualizations and geovisual analytics) (Helbig et al., 2017; Khan et al., 2013). In short, Smart Earth expand sensing modalities – tactile, auditory, even olfactory—by both humans and non-humans.

The most widespread application of this technology to date is "citizen sensing," which refers to intimate, experiential monitoring of environments by human users. Often, citizen sensing builds on existing citizen science initiatives, including those administered by non-governmental groups like the Citizen Science Center (2017) and government agencies like the Environmental Protection Agency (2013). As Gabrys (2016) suggests, "citizen sensing" can be usefully understood as a subset of broader phenomenon of citizen science: "research projects in which the public is enlisted in scientific endeavors" (Hochachka et al., 2012, p.130; cf. Snyder et al., 2013). In Smart Earth, citizen sensing has become a privileged means by which IT-enhanced data collection, learning, decision-making, and participation scales up from discrete local encounters to governance initiatives.

To improve the quality and usefulness of citizen-sensed data, and to validate it against third-party critiques, scientists are now devoting vast resources to training practitioners and elaborating research programs designed for non-experts (e.g. EPA, 2013; ONC, 2014; see also: Kinchy et al., 2014; Lave, 2015). By channeling sensing efforts into area monitoring, animal tracking, or impact assessment, citizen-sensing not only facilitates environmental governance and reduces institutional overhead (citizens are rarely compensated for their efforts in these schemes), it also helps to resolve one of the central challenges for Smart Earth: data is accumulating much faster than computational processing capacity (Woodward et al., 2013; Starosielski, 2015). For many actors, the effective exploitation of such data requires new computational solutions – to which committed citizens appear ideally suited (Goodchild and Glennon, 2010; Gabrys, 2016; Matabos et al., 2017).

Marine-related activity is revealing for the way such "citizen sensing" activities are being solicited in coastline-areas – environments undergoing rapid change and populated by new environmental "risks" (e.g. marine debris, oil spills, whale-vessel strikes). In North America's Pacific Northwest, coastal residents have become central in efforts to construct the "Smartest Coast in the World" (D. Moore, 2015a). Likewise, in China we find growing efforts to utilize citizen capacities to improve "overall marine operational situational awareness" (Heesemann et al., 2014, p.153; See: Guo et al., 2010, 2017). The opportunity to "sense" and not merely "collect" data is a highly relevant enticement within these schemes. Sensing becomes a privileged means to attract and intrigue non-expert researchers about changing littoral regions. For example, the Ocean Observatories Initiative (OOI) entrains viewers to its websites to listen to underwater sounds captured by hydrophones in real time.[1] Hydrophone deployment and (ostensibly) public monitoring activities are a central part of ONC's ECHO partnership (ONC, 2014), which is being touted across the marine research community (Ritts, 2017).

The worldwide growth of Smart Earth technologies potentially converts every citizen into an environmental sensing device (Goodchild, 2007; Elwood and Leszczynski, 2013; Georgiadou et al., 2014). This raises important ethical questions. What does it mean to perform sensory activity according to a pre-determined repertoire of "smart" practices? How are such determinations inflected by the structural inequalities of race and gender, and even species? Some scholars have worried that projects touting citizen sensing might do little to actually democratize decision-making (e.g. Whitman and Pain, 2012). Insofar as citizen sensing efforts like BirdReturn elide formal state regulation (Gabrys, 2014), or cultivate relationships with private entities, questions of arbitration, justice, and collective accountability are salient (Drusch et al., 2012; Georgiadou et al., 2014). In other words: what are the *citizen politics* of citizen science? How are "citizen-spokespersons" nominated and legitimated? How would conflictual forms of citizen science be managed via Smart Earth environmental governance?

Privacy issues are also significant. Smart Earth is characterized by new modes of citizen-activated management (e.g. Jepson and Ladle, 2015): for example, in projects like "A Smarter Planet" and CeNSE, individual citizens increasingly operate as essential operational and functional elements of environmental regulation. In transforming

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[1] See, for example: https://soundcloud.com/oceannetworkscanada.

citizenship into citizen sensing, the public becomes a constitutive element of an emerging "computational apparatus" (Gabrys, 2016). Citizens interacting with Smart Earth technologies will voluntarily submit to surveillance, providing data whilst having their online actions thoroughly indexed. Such “non-voluntary” systems of locational disclosure are built into many applications that individuals implicitly consent to when participating in Smart Earth activity – something Apple’s “Locationgate” scandal made abundantly clear (Cottrill, 2011). Because such disclosures cannot easily be controlled by individuals through settings adjustments to any one device, volunteered geo-data about Earth Processes enable “geosurveillance,” including by state security organisations and private contractors (Kitchin, 2014). There is thus potential for exploitative modes of recruitment and usage if proper checks are not established.

5. Conclusion

As explored above, Smart Earth technologies create the conditions for potentially significant shifts in environmental governance. Our review has provided insight into some of the ensuing challenges, debates, and critiques. In this concluding section, we briefly summarize key points and areas for future research.

Our analysis has emphasized the point (as reiterated by a significant amount of social science research) that better data does not necessarily lead to better governance. Indeed, we have suggested that algorithms might selectively reduce the sphere of possible intervention and analysis within a particular landscape. Mitigating against this tendency for the purposes of robust citizenship as well as sustainable ecosystem management requires democratizing access to environmental information, the nature of which is constantly evolving in light of technological change. In parallel, a comprehensive analysis of regulatory gaps is required, aligned with an analysis of the growth in integrative architectures currently being positioned as global frameworks for storing, analyzing, and disseminating Smart Earth data. In this context, a more comprehensive understanding of Smart Earth requires analysis of the changing nature of multi-actor and multilevel environmental governance—a key point, but one which was beyond the scope of this meta-review.

Another key gap in the literature is a critical analysis of the role of the state, historically a key player in facilitating multi-scalar processes of environmental change (Robertson and Wainwright, 2013). In Canada for instance, it is notable that the Smart Oceans™ initiative enjoys considerable state support; and harmonizes both with state regulatory goals (e.g. *Oceans Protection Plan,* 2016), and with state-led efforts to commercialize Canada’s marine technology sector (National Research Council, 2007; Strangway, 2013). Future work needs to critically evaluate the role of the state in enabling Smart Earth processes in different geographical and cultural contexts; for example, China has been extremely active in Digital Earth initiatives (Guo, 2012).

Further research is also required on the political-economic dimensions of Smart Earth governance. For example, Smart Earth creates not only new ways of sensing and administering environments, but also new categories of environmental assets. Some scholars have been concerned by the possibility that Smart Earth technologies may be harnessed to increase the efficiency of resource extraction, rather than serve environmental conservation purposes (J.W. Moore, 2015b; Malm, 2016; Demos, 2017). Further analysis on these issues could usefully draw upon debates of evolving environmental governance frameworks, including debates over Schwab’s (2017) “Fourth Industrial Revolution” as well as the politics of adaptive management and resilience (Walker et al., 2004; Rockström et al., 2009), multi-scalar environmental governance (Bulkeley, 2005; Cash et al., 2006), and network fragility (Graham, 2010).

Questions of ethics also merit more scrutiny. Smart Earth governance implies a shift not only from “government to governance”, but also from “manual to automated” eco-governance. Emergent regimes of state-sponsored surveillance consolidated around environmental big data – such as the Smart Oceans^{TM} project noted above – are mobilizing in support of security objectives rather than equitable access or efficiency (Amoore, 2013). Smart Earth also raises fundamental issues of socio-environmental justice. Elderly residents and those unable to own a smartphone face diminished opportunities to participate in Smart Earth governance since they “do not [necessarily] register as digital signals” (Crawford et al., 2014, p. 1667). Such social inequalities risk becoming entrenched through iterative forms of Smart Earth governance. As Leszczynski (2016) explains: “Algorithmic governmentality cannot divest itself of actual realities of socio-spatial stratification to which the derivative is theoretically indifferent” (1693).

Last but not least, issues of Smart Earth-generated e-waste (Cubitt, 2017) promise to be major problems in the coming years, and case studies of these issues (and their solutions) are scarce to date. Smart data will be derived from an expanded array of sensors, continuously sampling the physical world; its processing will in turn require real-time big-data analytics with greater energy demands. Innovation in batteries, power-saving technologies, and backups will be increasingly essential to the functioning and performance of “actually existing” smart grids, app-based conservation efforts, and the like (Shelton et al., 2015). E-waste will also pose new ecological problems for system managers and government institutions. There are considerable problems inherent in the Smart Earth proliferation of screen-based technologies, owing to their material externalities. A 2015 report by the Natural Resources Defense Council (NRDC) found that the idle-load electricity demands of digital consumer electronics (televisions, computers, printers, game consoles, etc.) accounted for 51 percent of an average American household’s energy budget (2015). An earlier report (Natural Resources Defence Council (NRDC), 2012) noted that 85 percent of electronics are now thrown out rather than recycled, leading some to calls for North Americans to adopt the radio in the place of the television, as the former creates substantially lower ecological costs (e.g. Smith, 2015). However, our review did not identify a single academic publication quantifying the e-waste associated with Smart Earth—a significant gap.

Given these concerns, Galaz and Mouazen (2017) are well-justified to call for a code of conduct (which they term a “bio-code”) that allows citizens and institutions an opportunity to take stock of the proliferation of new social relationships and ethical challenges created by Smart Earth forms of governance. Data-sharing policies and ecological measurements standards, key mechanisms by which Smart infrastructure attains the obscurity its planners routinely “seek” (Jackson and Bobrow, 2015, 1770), require new forms of visibility in public education and debate. Jasanoff’s (2003) demand for “technologies of humility” continues to resonate as a forceful appeal for new kinds of mergers between “the ‘can do’ orientation of science and engineering” and “the ‘should do’ questions of ethical and political analysis” (244). In this framing, ethics is not an “after thought” or addition to design but a crucial input across the life cycle of a given system—particularly one as ambitious and far-reaching as Smart Earth.

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