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Environmental Virtual Observatories (EVOs): prospects for knowledge co-creation and resilience in the Information Age

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Developments in technologies are shaping information access globally. This presents opportunities and challenges for understanding the role of new technologies in sustainability research. This article focuses on a suite of technologies termed Environmental Virtual Observatories (EVOs) developed for communicating observations and simulation of environmental processes. A strength of EVOs is that they are open and decentralised, thus democratising flow and ownership of information between multiple actors. However, EVOs are discussed rarely beyond their technical aspects. By evaluating the evolution of EVOs, we illustrate why it is timely to engage with policy and societal aspects as well. While first generation EVOs are primed for scientists, second generation EVOs can have broader implications for knowledge co-creation and resilience through their participatory design.

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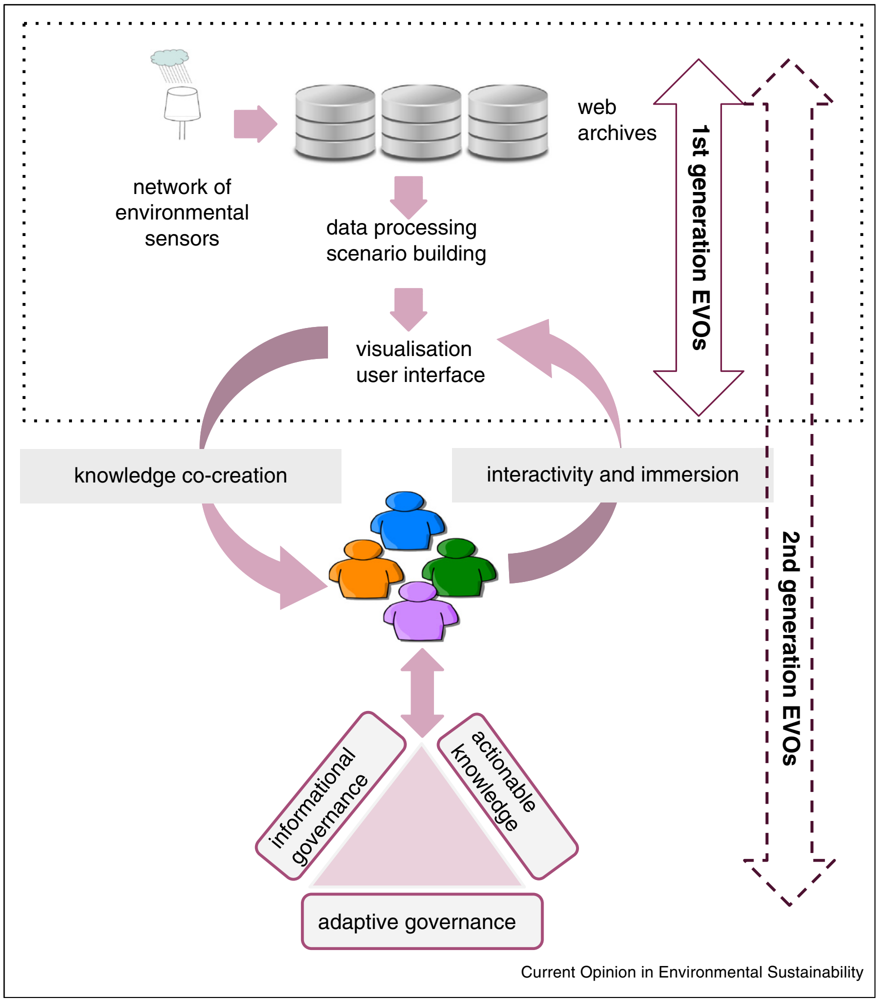
Introduction

Creating conditions that allow for the exchange of knowledge between scientists, decision-makers and citizens is becoming increasingly necessary for building resilience and responding to environmental change [1,2•,3,4,5••]. In this context, emerging open-technology approaches can be of added value by removing institutional and geographical barriers associated with information flows. Recent technological innovations in networking and computing such as Web 2.0 that re-conceptualises the Internet as a service, bring a new generation of data accessibility and interactive models embedded in virtual environments, closer to end users [6].

We use the concept of Environmental Virtual Observatories (henceforth EVOs), to describe the emerging suite of information gathering, processing and dissemination technologies (infrastructure, tools and software) supported by the World Wide Web that can enable cross-fertilization of different sources of knowledge on shared virtual platforms. Projects, such as the UK Natural Environment Research Council-funded Virtual Observatory and the US National Science Foundation Earth Cube initiative, have been purposively designed to provide ways of making information more readily available at different scales and to different types of users [6–8]. The openness of a web-hosted platform also facilitates the implementation of functionality beyond information access, such as interaction between users and scientists, and between users themselves. EVOs are in theory a platform that is neutral to social and knowledge ranks, as well as working styles. This allows both for anonymity and same-time and different-time (thus synchronous and asynchronous) collaboration among the various users [9]. As such, it provides an alternative or complement to labour-intensive contact-based research, and a real possibility to turn the typical top-down flow of information from scientists to users into a much more multi-actor dialogue. This shared virtual space makes it possible for multiple actors to participate actively in the social and scientific processes of knowledge co-creation, sensing, data processing and visualising the environment, in different arenas of environmental governance.

In this article we propose a conceptual distinction between what we define as first and second generation EVOs. First generation Environmental Virtual Observatories (the upper tier of Figure 1) consist primarily of technologies to support the scientific process of knowledge creation and mainly target scientific audiences. Up

Figure 1



Critical features of first and second generation Environmental Virtual Observatories.

to the time of writing this article, this has been the prevailing EVO design approach, whereas we will argue that it is now becoming more timely to explore further the design of what we have termed second generation EVOs. These are EVOs that compared to first generation EVOs, have a stronger focus on the processes of knowledge co-creation and interaction between stakeholders. Their success is largely based on the engagement of a variety of stakeholders. A further development of this knowledge co-creation aspect is that it can lead to EVOs attaining greater relevance in both debates as well as the practice of governance (i.e. the informational governance, adaptive governance, actionable knowledge triad outlined in the lower tier of Figure 1).

The article is structured as follows. First, we draw upon existing bodies of evidence on how EVOs are implemented currently as technology-based platforms for environmental decision support. This forms a critical discussion of knowledge generation and information exchange in first generation EVOs. Secondly, we describe opportunities that allow the transition to second generation EVOs. These are more participatory and purposive tools, capable of addressing a range of social and environmental objectives discussed in the second part of the article. In the conclusion, we describe both the transformative possibilities of EVOs as well as potential areas of caution in mainstreaming their future operationalisation.

Knowledge co-generation and exchange in first generation EVOs

The architecture and informational base of EVOs

At the core of EVOs are environmental observations, whether physically measured or derived. Data sources of EVOs typically consist of sensor networks, processing algorithms (e.g. environmental models), and their interoperability. The early incentive driving EVO development can be traced back to how scientists, particularly those engaged in environmental modelling, sought to maximize the opportunities afforded by new technologies such as cloud computing to support a better characterisation of natural systems. Dubois *et al.* [10] argue from an ecological perspective that, while historically better conceptualisation of the environment has relied on altering existing models or starting from scratch, current technologies allow for a third option of interlinking various contemporary models from multiple disciplines to optimize the search for answers to increasingly complex questions. In addition, the Internet further facilitates greater access and interaction between models and data archives [11]. This could allow for a user to customize the data and model selection from a pool to address specific questions. Significant challenges still exist, nevertheless, to make the integration seamless due to the slow development and adoption of standards in the data and model sharing. Furthermore, the web-based nature of EVOs can extend the possibilities of not only discovering legacy data, but also for 'big data' harvesting of, for example, geotagged photos and information flows from social media such as Twitter feeds. As access to EVOs can increasingly be established at a lower cost, the enabling structures for information flow pathways that have the potential to involve and benefit non-experts are therefore becoming more clearly distinguishable.

Communication of knowledge and information

EVOs enable rapid exchange of new information and decentralisation of information flows from various data archives and sensors, whether ground-based or remote, to any web-enabled device such as computer tablets and smartphones. A review of the first generation EVOs (see also Table 1) indicates wide-ranging applications as a decision support tool for the management of water resources, natural hazards and biodiversity. These technologies enable integrated representations of complex, multi-dimensional environmental processes, for instance, visualisation of flooded areas in multiple river basins or large scale weather systems.

The informational base (i.e. the web archives in Figure 1) of first generation EVOs is often scientific and spatial in origin. Data discovery and processing (environmental modelling) are hidden from the user, who navigates the virtual system and test scenarios by means of an interactive,

Table 1

Types of EVOs and properties of interest for knowledge co-creation and resilience

Classification	Description	Properties of interest	Sources of uncertainty	Examples
Environmental sensor networks	Technologies that support measurements of the physical environment	Decentralised communication of observations	Measurement errors (biases, equipment failures)	Weather stations, Earth-observing satellites
Data and knowledge hubs/portals	Web-hosted platforms that allow upload and download of content	Openness, anonymity, (a-) synchronicity	Unverified content	EPA STORET/WQX[a] Data Observation Network for Earth (DataONE)[b] USGS National Water Information System[c] EarthCube[d] WeAdapt[e], Mountain Observatories[f]
Environmental data visualisation and monitoring platforms	Web-hosted platforms that enable visualisation of spatiotemporal data on real-time and non-real time basis	Openness, timeliness	Errors from interpolation and rescaling of measurements	Weather forecast websites NCSA Virtual Sensor System [12] TELEIOS [13] Mid-Atlantic Watershed Atlas [14]; World Bank's eAtlas[g]
Environmental modelling platforms/decision-support systems	Web-hosted platforms that allow exploration and analysis of data under various scenarios/decision pathways with partial or total control over the scenarios and methods of analysis	Openness, anonymity, (a-) synchronicity, feedback loops, collaborative learning	Errors from interpolation and rescaling of measurements, simplification of known processes, and non-representation of unknown processes.	EVOp [15] Water2Invest [16] eHabitat-GEOSS (Global Earth Observation System of Systems) [10] BioVel [17] Model Information Knowledge Environment (MIKE) [18] Water World [19]

[a] Source: http://epa.gov/storet/; URL snapshot, https://archive.is/OlmOj [archived 09.06.15]
[b] Source: https://www.dataone.org/; URL snapshot, https://archive.is/k50Ep [archived 09.06.15]
[c] Source: http://waterdata.usgs.gov/nwis; URL snapshot, https://archive.is/A0Tp4 [archived 09.06.15]
[d] Source: http://earthcube.org/; URL snapshot, https://archive.is/1XQrn [archived 09.06.15]
[e] Source: https://weadapt.org/; URL snapshot, https://archive.is/4imAV [archived 09.06.15]
[f] Source: https://www.google.com/maps/d/u/0/viewer?mid=zhfDZt-F7c_g.k9ONzFyPYChQ; URL snapshot, https://archive.is/q08Dg [archived 09.06.15]
[g] Source: http://data.worldbank.org/products/data-visualization-tools/eatlas; URL snapshot, https://archive.is/VffzZ [archived 09.06.15]

visual interface. From large scale maps to detailed area/topic-specific information in the form of texts, graphs, and charts, users can zoom in and out of different levels of information richness through the point-and-click facility. Video-graphical forms of communication are also used, for example real-time webcam videos (e.g. observation of water level in the river in EVOp [15]), as well as user tutorials or introduction videos.

From the perspective of the user, it easily becomes clear that visual representation of information is a fundamental component that can serve to enhance or limit the effectiveness of EVOs (depending on how it is designed). Data visualisation is the means by which the users interact indirectly with environmental observations and models. An effective visualisation can help disentangle complex raw data and display it in a more understandable way. If carefully designed, visualisations can increase the human capacity to process and retain complex information and reduce cognitive workloads, for example, by clarifying patterns in parallel datasets. In some cases, they have also been used to attempt to give users a better grasp of the limitations associated with the presented information, for instance by visualising dynamically the uncertainties emanating from model assumptions and errors [20,21] (i.e. sources of which are summarized in Table 1). However, despite EVOs broadening access to scientific information, the value of visualisations and graphics is rarely considered on an equal basis, despite recent developments in visualisation expertise,[1] software and Web technologies (see also section 'New opportunities for fostering user interactivity and immersion'). For example, users are assumed to have the same level of scientific literacy and respond similarly to geospatial visualisation and line charts. Consequently, even if scientific information becomes more widely distributed on the basis of EVOs, it may still remain broadly inaccessible to different users, particularly non-scientists, because their way of viewing, interacting with, and sharing information has not been sufficiently reflected upon in the design [22••].

Furthermore, given the focus of first generation EVOs on the integration and communication of scientific databases and models, local knowledge is often absent. This does not necessarily imply a shortcoming in first generation EVOs, which have made significant contributions to knowledge creation and dissemination. But in contexts where co-generation of knowledge is relevant, we identify still unexplored opportunities to engage with new disciplines and users who may not be experts but own valuable knowledge (i.e. bridging the gap between the top and bottom tiers in Figure 1). In light of this, we find that significant opportunities exist to advance EVOs in such a way so that they can function as knowledge co-creation platforms from which different users can benefit. This of course requires re-defining to some extent the purpose, scope and user environment, which we explore in more detail in the subsequent sections.

Environmental decision-making implications of second generation EVOs

Actionable knowledge generation and dissemination

First generation EVOs have placed less emphasis on how enhanced participation of a variety of users can be achieved via a virtual environment. In many cases, information generation and dissemination projects particularly in the arenas of local community empowerment and environmental management assume a strong knowledge creation component but in reality do not always succeed in generating actionable knowledge [23].

Despite considerable progress in recent years, there are still cases of environmental information and dissemination programmes in which certain groups of people are not (or under-) represented. As a result, important aspects of those people's lives and environmental conditions are still not assimilated. This is particularly relevant for EVOs that exist on the interface between scientists and non-expert users of EVOs (e.g. farmers, water users or other types of local communities that may typically stand to benefit from EVOs). Given the high diversity of user backgrounds, perspectives and roles in such interfaces, it is important that any of the information presented in an EVO is properly contextualised, for instance, by exchanging demand-driven information and developing environmental scenarios (i.e. about crop choices or irrigation practices) that reflect end-users realities [24].

EVOs are designed with a goal to widen access to environmental information, while their potential role in facilitating the creation of actionable knowledge in environmental governance contexts still remains largely unexplored. This is an area that may require more systematic reflection at the technology pre-design and experimentation phase. More emphasis can be placed for instance on the tacit knowledge of users by using methods such as cognitive mapping [25•]. Stakeholder involvement exercises such as focus groups, games and experiments, and interactive group exercises are also an important component of actionable knowledge generation. These types of stakeholder engagement activities have been used for instance successfully in the case of the Rönneå Catchment Dialogues in Sweden in order to identify a sustainable water management strategy for the Rönneå catchment [26]. Participatory modelling experiments in small rural towns in the UK also give valuable insight into how rebuilding computer simulation models to suit specific contexts and needs can support the re-distribution of expertise between scientists and affected

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[1] Some examples of emerging expertise in visualisation include the GeoViz toolkit, User experience design (UXD or UED) and Information Visualisation (InfoVis).

publics in relation to environmental issues of local concern, such as flood risk [27].

A key challenge for making this type of system operational as an EVO platform is bridging the gap between qualitative data (such as local observations, citizen-generated data and perceptions data) and the quantitative data systems that are typically used in decision support tools [28]. EVOs implicitly assume inputs of parameterisable scientific knowledge. This is in part manifested in the form of relatively well structured data sets produced through established scientific methods, such as monitoring of hydrological, ecological or environmental variables (e.g. precipitation, streamflow, vegetation dynamics etc.). Cloud computing, social networking, and interactive web app design may foreseeably support different modes of data collection that are more sensitive to user experiences as well. Recent rapid advancements in related research areas such as data mining, information visualisation, and interaction design, also push the envelope of what can be communicated with data. However we see a much larger potential and scope for EVOs to enable the production of actionable knowledge by bridging different expert disciplinary communities as well as non-experts in technology co-design processes.

Generating actionable knowledge necessarily implicates social processes that operate outside virtual information exchange spaces. Understanding these social processes requires direct engagement with users as well as real world experimentation. Participatory methodologies such as Participatory Action Research (PAR) have been recognised for some time for enhancing bottom-up stakeholder driven investigation however have not so far been considered in EVO applications. Allowing for more bottom-up engagement with stakeholders can play an important role since it can capture how EVO development can better integrate user needs and local experiences. Efforts to mobilize bottom-up engagement with stakeholders prior, during and after the design of an EVO is also more likely to ensure reflexivity is built into knowledge co-creation processes and that different contextual factors in knowledge creation, including cultural interpretations, value systems and the social or biophysical environments in which knowledge systems are embedded, have been considered [29••]. At present as there is no roadmap or single methodology for generating actionable knowledge in EVOs, it is therefore anticipated that this will require that a degree of flexibility, openness to alternatives and iterative learning to become in-built to the design of EVOs.

Embedding EVOs in multiple modes of governance

The governance implications of EVOs are potentially transformative. On one hand they fit with the notion of informational governance [3], whereby flows of information pertaining to environmental decisions are no longer shaped by single entities (i.e. the state or the university) but instead take place across multiple actors and networks (i.e. including a stronger representation of civil society). On the other hand, EVOs are also compatible with the adaptive governance approach that recognises the role of multiple knowledge sources in dealing with environmental complexities and uncertainties [30]. Strengthening the monitoring, measurement, and collection of environmental information are all important conditions for adaptive governance. However this is an area that is still largely unexplored in terms of the role that information and communication technologies such as EVOs can play in the medium to long-term future.

The crucial role of environmental information and knowledge is highlighted within the literature on governance of social-ecological systems. A key issue in this literature is the capability of adaptive governance to guide social-ecological systems towards greater resilience of interconnected human and environmental systems (i.e. the capability to (1) resist shocks, (2) adapt flexibly to constantly changing conditions and (3) to transform when required, in order to keep fulfilling basic ecosystem functions and services) [4]. Altogether, these capabilities are essential for fulfilling basic social-ecological functions and are particularly relevant where decisions need to be taken under high uncertainty, in a world that changes both slowly and abruptly in unpredictable directions. Effectively, when it becomes nearly impossible to predict what exactly is coming, observing and understanding developments as they unfold becomes paramount. EVOs can be implicated in guiding and shaping important governance decisions, by linking for instance local level data and knowledge with global data into environmental models. EVOs in the context of adaptive environmental governance can thus be viewed as useful elements of polycentric institutional arrangements for real-time monitoring, cross-level and cross-scale information sharing, engagement and interaction between individuals, organizations, and agencies at multiple governance levels.

Learning is another important condition for safeguarding resilience. Insights from scholars that have analysed learning processes suggest that different degrees of learning can be distinguished [31]: single loop learning, referring to incremental changes; double loop learning, referring to reframing guiding assumptions; and triple loop learning, referring to a transformation of the structural context. All of the aforementioned processes rely on the quality of environmental information. However, the availability of uninterrupted good quality information may often be hard to attain. EVOs can therefore become the medium through which different types of learning processes can become realised. Remote mountainous regions for example, that are especially susceptible to changing environmental dynamics also happen to be almost invariably data scarce [32]. There are very few

Figure 2

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A design concept of a dashboard-style web application for smallholder farmers in Africa. Accessed with permission http://blog.vizzuality.com/post/114042422481/thought-for-food; URL snapshot: https://archive.is/80jXY [archived 09.06.15].

observational data to assess changing socio climatic trends and variables[2]. This is partly because government institutes tend to give high-elevation sites a lower priority because of reasons including costs and logistics. One way in which EVOs can support incremental learning processes in such regions is by supporting the development of natural resource management plans that are informed not only by analyses of global climate science predictions but also by local hydro-meteorological data as well as local observations of changes in social and economic conditions[3]. EVOs that have been designed in a participatory manner with local communities will ensure that the information will be accessible for a wider range of actors. Decision-making bodies can utilise this information further to inform local planning strategies and iteratively use these analyses to inform decision-processes at different levels of governance, from the district and village to the level of the household.

New opportunities for fostering user interactivity and immersion

Interactivity and immersion is still lacking from first generation EVOs but could have a more central role in second generation EVOs. Open web technologies have improved capacities to create visualisations that integrate exploratory tools and generate tailor-made graphics. Linking data, models and visuals within an analytical tool, can encourage audiences to 'learn by doing' [22••]. If this is achieved, users are able to develop a tailored mental model of, what is often, multi-dimensional information. Rapid progress in this field could help signal the transition from first to second generation EVOs.

Putting emphasis on storytelling in this context offers both a 'bridge' as well as a concrete collaborative activity for users to save, share and compare ideas [33,34]. It

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[2] Recently, the Mountain Research Initiative (MRI) (see also, http://mri.scnatweb.ch/en/), established a global network of environmental sensor networks in mountain regions with the aim to improve environmental data and knowledge relating to mountain regions.

[3] The Mountain Social Ecological Observatory Network (MtnSEON) (see also, http://webpages.uidaho.edu/mtnseon/) is a good example of a recent platform which aspires to combine multiple sources of knowledge on how processes function within and between ecosystem and socio-economic elements in the context of complex mountain landscapes.

provides necessary context as well as linkages with varieties of tacit knowledge and introduces emotional connectivity within knowledge exchange. Incorporating uncertainty into EVO design has traditionally been challenging but recent technological developments are making it easier for designers to incorporate uncertainty into graphics, for example redesigning glyphs, adding interactivity or using a different type of visualisation completely [22••].

Advances in visualisation are enabling data to be presented in more visually appealing and innovative ways. Informative and robust displays can be extracted from subsets of data or specific model parameters to produce digestible and salient storylines, which ultimately assist retention and learning. These developments on the one hand encourage access to non-expert users, but on the other run the risk of overloading communicators with limitless design choices, allowing them to frame data in multiple ways, open to a plethora of interpretations [33,35]. For this reason, there is an increasing number of initiatives for developing engaging experiences tailored for a heterogeneous range of users. One instance of this is a dashboard-style web application that empowers small-holder farmers in Kenya with access to different types of data including weather forecast and market data[4] (see also, Figure 2). Another example is an interactive web exhibition to inform and enthuse general audiences about some of the world's least-known endangered animal species. The website allows visitors to browse through 30 animated polygons representing each species and to discover related conservation stories, videos, web links and basic statistics[5]. By focusing on informed visualisation design, improved access to data and user-driven tool development, the capacity of non-expert users to explore and translate most relevant information into actionable knowledge, becomes significantly enhanced.

Conclusions

EVOs can enable rapid exchange of new information and open new information flow paths. We have used the distinction between first generation and second generation EVOs to illustrate some ways in which EVO applications can be expanded (see also Figure 1). This is an issue that is highly relevant to data and information coordination and is fundamentally important to sustainability research, even though it still gets very little scholarly attention. The topic is also very rarely addressed as a global change issue, and even more rarely linked to discussion about resilience, governance, inclusive participatory processes and scientific responsibility.

In this article we have demonstrated that some of the most promising advancements in harnessing information and communication technologies are likely to emerge when technical and scientific aspects become balanced with societal needs and responses. Links also exist between EVOs and informational governance (this issue). EVOs align well with informational governance particularly in terms of opening up alternatives and accelerating information flows. Furthermore, EVOs align well with the adaptive governance concept of polycentricity, specifically; facilitating information exchange in a decentralised, multi-level and multi-directional manner. EVOs offer important potential as open collaborative tools, combining principles of interactivity, polycentricity and (a-)synchronicity, and thereby enhancing opportunities for improved knowledge co-creation and resilience.

Despite their potential, the design and implementation of EVOs may not always be well aligned with the purpose of community empowerment or resilience. They may become neglected or redundant, and this can be a problem particularly if they are designed from a supply perspective, that is without a clear demand. Furthermore, the inherent nature of EVOs assumes web accessibility and literacy as necessary preconditions for their use. While access to the Internet is expanding, the most fragile communities and environments may still be lacking computing infrastructure, and may have to rely on workaround technologies, such as mobile-phone technology or the radio. These types of alternatives to online portals have not been sufficiently considered in first generation EVOs but would need to have a more prominent role in second generation EVOs.

Caution is needed about being overly optimistic about the value of these technologies in the near future. The success of an EVO depends to a large extent on whether a participatory approach can effectively be adopted from an early stage, through an elaborate user consultation process. Open and inclusive participation in the entire EVO process needs to be better emphasised as well. More generally, the scope of EVOs also relates to the level of opportunity people have to actively participate in decisions that concern their livelihoods and local environments. Consequently, the usefulness of information generated or disseminated with EVOs increases when these actors become directly involved in generating the knowledge, such that it can be legitimately used to assess different livelihood options but also help evaluate preferences or decisions in challenging social-ecological situations (e.g. geographically remote and data poor regions).

Information access is not equally divided over the globe, or within countries or communities, and knowledge and

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[4] Source: "Thought for food – We're bringing satellite data to smallholders", Accessed with permission http://blog.vizzuality.com/post/114042422481/thought-for-food URL snapshot: https://archive.is/80jXY [archived 09.06.15].

[5] Source: "Species in pieces", http://www.species-in-pieces.com/ [accessed 09.06.15].

information are also an object of power struggle (e.g. when environmental knowledge and environmental information flows become monopolised or controlled by only a few actors) [2•,3]. The lack of data standards and sharing permissions, language and scale barriers between various environmental fields, and static visualisations of highly dynamic environmental processes are also manifestations of power struggles that can create additional barriers [36]. However, if and when designed and used well, EVOs have the potential to make science and data more transparent and accessible in a way that informs and empowers citizens, increases public confidence in scientific inquiry and data generation, facilitates collaboration and learning between diverse stakeholders, and provides a platform for direct feedback, commenting and rebuttal.

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- •• of outstanding interest

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