Assessing the Potential of E-Tools for Knowledge Sharing and Stewardship of Urban Green Infrastructure

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Abstract. Background: People caring for urban green infrastructure, not least urban trees, play an important role in maintaining the quality of the urban environment. But what happens when information processing and knowledge generation become digitalized? This study examines digital tools developed to provide knowledge support and with ambitions of inciting stewardship. It asks what understanding they draw on, what information they broker, and how they approach uptake and use of the content they provide. Methods: We analyzed 6 different e-tools within the context of urban green infrastructure in New York City, New York, USA. We conducted semi-structured interviews with the tool creators and assessed the e-tools themselves. Results: Our findings indicate that most e-tools are designed to provide access to different types of information about urban social-ecological systems and, passively or more actively, stimulate learning. In addition to rich, complex, exploratory digital learning environments, many tools combine virtual experiences with in-person training, workshops, and coaching. Conclusion: The observed hybrid approaches harness the power of digital platforms to enable diverse usership and share large amounts of data while employing more traditional on-the-ground organizing techniques and thus offer a way forward in an age of increasing dominance of digital data. Future research on e-tool usership, hybrid learning approaches, and connections to stewardship outcomes could enrich the understanding of how e-tools operate as well as their social-ecological potential and impact.

Keywords. Digital Tools; E-Tools; Knowledge Exchange; Stewardship; Urban Green Infrastructure.

INTRODUCTION

As urban populations continue to grow, demand for urban ecosystem services (ES), or the benefits people obtain from ecosystems (Corvalán et al. 2005; Haaland and van den Bosch 2015), increase. Green infrastructure is now used in dense urban areas as a tactic to increase critical ecosystem services, including improving quality of life for people and restoring ecological functions. Urban green infrastructure (UGI) emphasizes the management and production of ES, which can include producing local food and water (Gómez-Baggethun et al. 2013), reducing impacts of stormwater (Pataki et al. 2011), and regulating microclimate and urban heat island (UHI) effect (Gill et al. 2007). Managing green infrastructure is critical for sustainable, equitable cities. Meanwhile, the capacity of the system to generate these services can be diminished if not given the critical attention and management they require (Elmqvist et al. 2004).

We know that managers of UGI can extend beyond government to include the civic sector (Svendsen and Campbell 2008; Campbell et al. 2021), however, little is known about how these stewards engage in knowledge collection, exchange, and application (but see Silva 2017). Emerging examples of digital communication platforms, or e-tools, a term coined by Møller and Olafsson (2018), could provide additional support for participatory governance and management of UGI. The functions of these e-tools can include citizen science efforts but also range from collection of geographic information to land use advocacy platforms and even digital landscape planning tools (Møller and Olafsson 2018). Here, we seek to examine how e-tool platforms may contribute to stewards' knowledge systems for UGI management.

Knowledge Systems

Knowledge about ecology and the societal context is critical for management of UGI (Andersson et al. 2014).

Knowledge in the context of this paper refers to the information about and understanding of the stewarded social-ecological system (SES). It also encompasses the concept of learning or the capacity to respond to and internalize system dynamics (Cundill et al. 2015). Traditionally, conventional scientific methods are the most widely recognized sources of knowledge for the planning and managing of UGI (Chapin et al. 2009; Hansen 2014). However, a growing body of literature explores and acknowledges the validity and importance of more diverse knowledge systems. Local and Indigenous knowledge are now understood as key components for understanding and improving the governance of ecosystems (Yli-Pelkonen and Kohl 2005; Ballard et al. 2008; Tengö et al. 2014; Whyte et al. 2016). Additionally, tacit, or experiential, knowledge, or knowledge gained from hands-on practice, is also understood as a key product of and means for stewardship (Cooke et al. 2016; Silva 2017). Sustainability transformation literature offers an extended typology of knowledge, referring to system, target, and transformative knowledge (Hadorn et al. 2006). In order to investigate and classify the knowledge exchanged using e-tools, we employ here a conception of knowledge systems (Partelow and Winkler 2016) focused on these three knowledge types and also drawing upon Elinor Ostrom's diagnostic SES framework (Ostrom 2009). Partelow and Winkler (2016) apply these knowledge types to discuss what actors and change makers need to know to engage with or make changes to the system, which is often the goal of such e-tools. The three knowledge types are defined as follows (Figure 1):
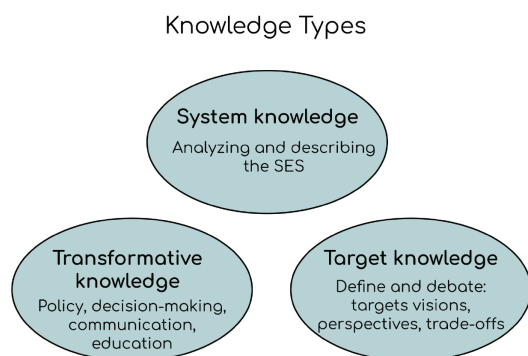

Figure 1. Three types of social-ecological system (SES) knowledge. This figure shows three classifications of knowledge as defined by Partelow and Winkler (2016). The knowledge types are not a hierarchy; they can exist in a system independent of one another, but considering the interplay between the three types of knowledge allows for an enriched understanding of an SES.

System knowledge is objective knowledge of social-ecological subsystems and components as well as their interactions, functions, processes, and interrelated dynamics, including aspects in relation to risk, uncertainty, and resilience (Partelow and Winkler 2016). System knowledge can be thought of as more "traditional" scientific-technical conceptions of the SES. This knowledge type is crucial for the governance of SES (Primmer et al. 2015), particularly when it can help to identify trade-offs between management for and production of various ES (de Groot et al. 2010).

Target knowledge can be described as subjective perspectives and deliberative and/or experienced knowledge relating to the implications, targets, visions, desired directions, and outcomes for SES. This can include the concepts of human well-being, conservation, justice, ethics, efficiency, and sustainability goals (Partelow and Winkler 2016). Target knowledge relates to system knowledge as it transitions beyond the understanding of the SES toward playing a more operative role in society (Fischer et al. 2015). Target knowledge tends to be understood more at the local scale, as it is often iterated in the process of discussion and decision-making between local stakeholders. This type of knowledge helps to inform "socially relevant and accepted decisions" (Partelow and Winkler 2016) that would be challenging to formulate using system knowledge alone.

Transformative knowledge is defined as the actionable pathways for implementing SES change and/or target knowledge through normative mechanisms such as policy, decision-making, education, communication, participation, and motivation (Partelow and Winkler 2016). In a planning context, transformative knowledge can be used as a mechanism to help varied stakeholders realize different values and perspectives and demonstrate particular needs (Hauck et al. 2013; Karrasch et al. 2014).

Communicating and Exchanging Knowledge

The effectiveness of any accumulated knowledge in a system depends greatly on how it is exchanged, who exchanges it, and how it is used. Here, we use the bidirectional term "knowledge exchange" in the place of learning, as it describes all "processes that generate, share and/or use knowledge through various methods appropriate to the context, purpose, and participants involved" (Fazey et al. 2013). Specifically, this term encompasses both the sharing of knowledge

but also the production of knowledge. Coproduction of knowledge is a process that can be nested under knowledge exchange and implies a process through which knowledge is produced through interaction with others. It often emphasizes the cooperation and the inclusion of multiple perspectives and backgrounds (Fazey et al. 2013). It is a term that allows for the inclusion of political goals, expectations, and societal norms that are inseparable from ways of knowing or accumulated knowledge (Muñoz-Erickson 2014). Knowledge brokers, which Bodin et al. (2006) describe as organizations or individuals that "gain access to many pieces of group-specific information captured inside the different groups, which allows the broker to synthesize a large knowledge pool…[and know] which groups or individuals to connect, how to connect them, and when," can play a key role in knowledge coproduction within networks of diverse actors.

How knowledge is exchanged can also affect how knowledge is accessed, consumed, generated, and applied. Science communication has traditionally focused on the information deficit model, whereby knowledge is disseminated in a one-way exchange (Ockwell et al. 2009). However, increasing knowledge coproduction opportunities, recognizing knowledge brokers, and increasing digital communication tools now offer two-way exchanges that can incorporate multiple voices and ways of knowing (Tengö et al. 2017; Falco and Kleinhans 2019; Norström et al. 2020). As such, civic science endeavors, which coproduce knowledge, offer a path forward for more effective science exchange (Simis et al. 2016).

Urban Environmental Stewardship and Knowledge

Civil society actors, or stewards, who engage in caring for local nature are often vital for the management of green infrastructure in cities (Connolly et al. 2013; Andersson et al. 2014). Urban environmental stewardship (UES) practices such as community gardening, neighborhood tree planting, and habitat restoration help provision ES and maintain biodiversity in cities (Goddard et al. 2010; Pataki et al. 2011; Sassen and Dotan 2011; Elmqvist et al. 2013; Krasny et al. 2014). Further, active engagement in UES may lead to positive outcomes for participants and their communities (Barthel 2006; Krasny and Tidball 2012; Andersson et al. 2014) and contribute to a larger civic environmental movement (Sirianni and Friedland 2005).

However, the capacity to actively steward is enabled by possessing all three types of knowledge, and in an increasingly modern society, urban residents may lack the experience, knowledge, skills, and access to engage in stewardship.

Peçanha Enqvist et al. (2018) conceptualize stewardship across dimensions of knowledge, care, and agency, defining knowledge as basic information about the SES, drawn from a variety of knowledge systems (e.g., Western science, Indigenous knowledge, experiential knowledge). Literature suggests that UES knowledge is shared and exchanged at the interpersonal level and through embodied experiences. McMillen et al. (2016) observed that community garden stewards shared and produced knowledge relating to horticultural practices, culinary expertise, and garden construction through a diverse process of collective communication, experimentation, and cooperation between gardeners. UES knowledge has also been described as collectively held memories about the structure, function, and/or change over time of the given landscape (Barthel et al. 2010). This "social-ecological memory" can be transferred between individuals and groups across spatial scales and over time through carriers. These carriers can include habits and routines; oral traditions; rules, regulations, and norms; physical artifacts; and external sources of knowledge (Andersson and Barthel 2016). In a study of stewardship knowledge exchanges, Silva (2017) found that stewards construct knowledge about practices through their work, but that issues such as the prevalence of transient volunteers and staff result in knowledge transfer loss. Silva also found that it was difficult for stewards to internalize knowledge from outside sources, particularly if there was too much information offered at once or the knowledge could not be directly applied to stewardship practices.

Digital Learning Environments

There is a growing concern about the disconnect of urban, digitalized residents and the dynamics of the biosphere—in cities and outside—expressed as an ongoing extinction of experience (Soga and Gaston 2016) and a decreased feeling of agency over the local environment (Andersson et al. 2017). At the same time, technological solutions have the potential to disseminate and produce knowledge about UGI and offer a novel platform for participation in environmental management and decision-making (Møller et al. 2018).

New media technology is rapidly introducing novel methods for online learning, planning, and managing of urban resources and coordinating collective action (de Lange and de Waal 2013). A growing body of research is exploring the conceptualization, development, and implementation of technologies that are empowering people to engage with and actively shape their urban environment (Paulos et al. 2009; Foth et al. 2011; de Lange and de Waal 2013). Apps, software, and other technology have opened the door for citizens to collect, process, and coproduce data as part of scientific inquiry (Silvertown 2009). Participation in these efforts has been shown to increase scientific interest and knowledge in community members (Evans et al. 2005; Bonney et al. 2016).

Studies have compared digital and analog knowledge exchange strategies, most frequently in the context of education and formal classroom or institutional learning. Meta-analyses comparing electronic distance education to learning from traditional in-person instruction have indicated that there is practically no difference in learning between the two (Bernard et al. 2004; Clark and Mayer 2016). However, the planning of the courses and quality of the teaching and learning activities are a significant factor (Muñoz-Erickson 2014). These studies concluded that the instructional method or pedagogical approach is far more influential on learning than the delivery method. However, there has been no study focused explicitly on digital knowledge exchange as it relates to urban environmental stewardship.

To address these gaps in the literature around knowledge types and knowledge exchange as it pertains to e-tools for stewardship, we examine a set of e-tools and their use by civic stewards to answer the question: "What type of knowledge sharing is being facilitated by e-tools, and how does this knowledge relate to stewardship of UGI?" We frame this question by applying Partelow and Winkler's (2016) conceptual model of knowledge systems for system transformation as a framework for discussing the knowledge needs for taking stewardship action in a complex, urban system.

MATERIALS AND METHODS

Limited research exists on digital knowledge sharing and how it relates to stewardship. Therefore, we chose an exploratory, qualitative approach to collect and analyze data on e-tools for UGI. We applied a case study approach (Yin 2009), selecting cases to be different and emblematic, providing conceptual insights into the development and use of digital tools for urban environmental stewardship (Silva 2017).

For each case, we examined an e-tool and its associated context. We chose to bound the selection of tools to those geographically connected to New York City (NYC). NYC is a complex urban system with significant environmental challenges and development pressures. It also has a large, well-established network of stewards that have been the subject of several studies (Connolly et al. 2013, 2014; Krasny et al. 2015; Svendsen et al. 2016; Silva 2017). These studies have classified NYC's stewardship network as vast and diverse, serving a variety of site types including community gardens, street trees, parks, and waterways. The size and formality of these groups can range from a few people and highly informal to large, well-established nongovernmental organizations (NGOs) with significant annual budgets. Additionally, NYC had a variety of existing e-tools focused on natural resource management that allowed us to select cases from across various site types. Focusing on tools developed in one city allowed us to control for factors such as local policy, site conditions, and social-ecological history. We opted to study cases that represented a variety of practices (tree care, gardening, and landscape planning) rather than focusing on a single type of practice on its own to derive findings that were generalizable to the broad landscape of stewardship behaviors. This variety in site types also represents a variety of ecosystem services such as regulating climate and UHI, local food production, and recreation opportunities. After a scoping review of e-tool platforms in NYC, we selected 6 intentionally different tools for data collection based on the criteria that they were tools built to be accessed digitally (on a smartphone or computer) and focused on urban green infrastructure (Table 1).

The study involved participant interviews ($n = 11$) and subsequent qualitative data analysis guided heavily by analytic induction (Bryman 2012). This research was subject to a full ethics review conducted by the Stockholm Resilience Centre. For each case, we interviewed tool developers. More specifically, interviews were carried out with representatives from each organization who played a key role in either the ideation, development, and/or current maintenance of the online tool. Interviews were conducted with two representatives of each case study except for one organization that declined to provide a second interviewee.

The interviews were semi-structured (Kvale 1994), which allowed for follow-up and probing questions and participants expanding on themes and sharing reflections throughout the interview. An interview guide was developed based on both the history and development of the e-tool as well as the types of knowledge being exchanged.

The interviews were recorded and transcribed, and a coding hierarchy was developed based on the theoretical framework. Interviews were first coded (using NVivo 12 analytical software) using Partelow and Winkler's knowledge system framework as an initial coding structure. Guided by grounded theory approach (Bryman 2012), the coding was captured in stages of successive coding carried out in three rounds. First, the data were coded descriptively to sort responses into statements about goals, aspirations, motives, or outcomes. Second, the data were

Table 1. Descriptions of 6 cases of e-tools for urban green infrastructure in New York City.

Name	Developer/owner	Organization type	Site type	Description	Intended users/ audience	Knowledge types exchanged on e-tool
Healthy Trees, Healthy Cities app	The Nature Conservancy in partnership with USDA Forest Service	International NGO and federal government	Street trees	An app that allows users to map trees, assess and track their health, detect pests, and track stewardship activity	Tree stewards, land managers	System, target, transformational
ioby	ioby	National NGO	Multiple site types	A civic crowdfunding platform for local community coaching and peer-to-peer learning for project owners	All civic stewards	Target, transformational
Natural Areas map	Natural Areas Conservancy and New York City Department of Parks and Recreation	Local NGO and city government	Urban natural areas	A map of the location, ecological composition, and condition of all forests, wetlands, salt marshes, and grasslands in NYC	General population	System
NYC Street Tree map	New York City Department of Parks and Recreation	City government	Street trees	An interactive map of every street tree in NYC including valuations of ecosystem services and a tree stewardship activity tracking feature	General population, tree stewards	System
STEW-MAP	USDA Forest Service, NYC Urban Field Station	Federal government	Multiple site types	A map of NYC area stewardship groups that displays general information for each group, their geographic "turf," and their network in relation to other stewardship groups	Land managers, all civic stewards	System
Visionmaker NYC	Wildlife Conservation Society	International NGO	Multiple site types	A mapping tool in which users explore the past and current ecological landscape of NYC and "paint" a vision of a new ecological layout while the tool calculates and presents the ecological trade-offs	General population	System, target

coded based on the three knowledge types, and finally, the transcripts were coded based on emergent themes identified during the first two rounds of coding.

RESULTS

The following results are structured around the three types of knowledge presented earlier in the paper: system knowledge, target knowledge, and transformative knowledge. Findings related to each of the types of knowledge are discussed below.

System Knowledge

Common among almost all the tools investigated was the sharing of system knowledge. In fact, this is stated as a primary goal of most of the e-tools. The type of system knowledge varied across the cases. However, certain patterns and overlaps in specific social-ecological information were observed. Before addressing these classifications of system knowledge, it is important to explain that ioby is an outlier. While it is not exchanging system knowledge, per se, a pillar of its platform is elevating the role of locally held system knowledge and creating pathways for action in communities. As an ioby representative explained,

> *"We were kind of founded with the idea that neighbors know best,…but they often lack the resources…so we can really serve as a bridge for people who already have the ideas and have the network and have the motivation and need a foothold."*

ioby's model is built around the concept that there is a wealth of system knowledge within communities, and its platform helps build and share target and transitional knowledge in order to operationalize change. We will examine ioby's role in elevating and sharing locally held knowledge further when discussing target and transitional knowledge.

Structure and Function of UGI

Several of the e-tools including the Natural Areas map, the NYC Street Tree map, and Visionmaker NYC focused on exchanging knowledge about the spatial distribution, ecological composition, and function of green infrastructure in New York City. These included the location, species, and size of trees; the location and ecological composition of natural areas; and the past and present ecological mosaic of the city at a landscape scale. Sharing this information was, for the most part, motivated by the fact that the agency had a data set and saw value in sharing this data to the public. Furthermore, the developers of e-tools that were created by or related to the municipal government saw that there was value in open data, not only to educate the public about UGI resources but also to create a more transparent relationship between UGI managers and the public to drive data quality. As a developer of the NYC Street Tree map explained:

> *"We all want to have up-to-date data on street trees. We can do that partly by surfacing it, sun lighting it and making sure it's available in a way that people can really understand how it's being used…so it's really starting with the idea that the value in the data itself for managing the urban forest comes from making sure that more and more people are invested in how it's being used."*

The above quote illustrates an understanding that simply providing open data to the public does not create investment or accountability. The developers of the e-tool worked to present the data and develop functionalities in the tool that would foster interest and investment in the urban forest by its users.

In addition to the content and configuration of UGI, 2 of the tools also focused on defining and describing threats to specific ecologies. The Natural Areas map outlines threats such as invasive species and herbivory. The Healthy Trees, Healthy Cities (HTHC) app presents a pest detection protocol developed by the US Forest Service to help users identify and detect harmful pests that plague urban trees.

Management Regimes

The 2 e-tools developed by or in partnership with municipalities, the Natural Areas map and the NYC Street Tree map, also had a function of sharing data on the management of green infrastructure. In both cases, the two apparent goals of sharing this type of data were to create transparency in government and reveal the extent and necessity of these management activities. The developers explain that, often, the public perceives UGI such as trees as self-sustaining entities. They expressed that in cities, many people don't understand how highly planned and managed UGI is, as it resembles more "emergent" natural systems that people may be more familiar with. For this reason, sharing data on how much planning, effort, and funding is needed to maintain various UGI was a key desired learning outcome for the users.

Complexity of System Knowledge

In most of the cases explored here, scientists and natural resource managers are responsible for ideating and overseeing the creation of the digital tools to share their vast data resources with the public. This has created a challenge in how much information to share and in what format. Some of the tool developers even went so far as to describe their interface as "overly-complex" and "obtuse," and that "the complexity of the data affects a lot of the usability of the tool." As an example, Visionmaker NYC struggled to display a wide array of rich ecological data values while still making their tool user friendly. A Visionmaker NYC developer explained that there's no way to "gamify" complex ecosystem problem solving. He expressed that many people expect something to be fun and simple to use if it is on the internet but concluded that:

> "If you really want to envision a future for your area and understand what's the effect of your vision, it actually takes work. I mean no matter how easy we make it and how fun and everything, it's work."

STEW-MAP struggled in the development of their online tool, especially because the data they wished to share were collected by a limited scientific survey and therefore did not easily lend itself to a usable digital data set. As one of the lead scientists remarked:

> "This tension between showing the details of an individual group and showing the cumulative patterns is something we're constantly struggling with, and it affects the functionality of the software."

Many of the other e-tool developers reiterated this tension between presenting a highly complex, scientific data set and making the tool technologically functional and usable to a layperson.

Target Knowledge

Exchanging target knowledge speaks to tool users developing an understanding of their own embedded values and those of others. All e-tools named the development of target knowledge as a goal or an aspirational outcome of the platform, however, many of the tools had not yet integrated that knowledge type into their platforms. A common rhetoric amongst most of the developers and managers was the hope that by exposing users to system knowledge, they would have an opportunity to internalize this knowledge and develop new values and attitudes about UGI. The Visionmaker NYC developer acknowledged the important role they believe that system knowledge plays in developing target knowledge by saying:

> "Having better information leads to better decisions…rather than [having] actors with particular agendas or incentives looking at different kinds of data."

Some of the e-tool developers expressed a belief that learning about the ecological system would inspire an ethical incentive to participate in stewardship. System knowledge about threats to UGI, for example, is believed to inspire a desire to care for or protect these resources. The developers of the Natural Areas map explained that through presenting the primary threats to a particular natural area, users may become interested in helping to combat those threats. In the case of the NYC Street Tree map, the sharing of information about ecosystem services, specifically in monetary terms, is believed to encourage a development of personal value for trees, particularly more mature trees that produce more ecosystem services. Their hope was that this understanding would then translate into a desire to steward the urban forest. In the case of STEW-MAP, this was discussed in terms of individual stewards and stewardship groups being able to see the work of others in their community and feel inspired.

Stewardship Actors and Embedded Values

The NYC Street Tree map, STEW-MAP, and the HTHC app enable users to measure, track, and/or share stewardship activities or describe the larger network of stewards of the landscape. On the NYC Street Tree map, this allows all users to see where stewardship is happening across the city's urban forest and allows stewards to coordinate efforts amongst one another.

A common motivation for sharing this type of data was a desire to legitimize and celebrate the contribution of stewards. Developers mentioned that the work of stewards is often only noticed or appreciated at the local scale, and in mapping these grassroots efforts collectively, e-tools have the power to elevate the recognition and legitimacy of local stewardship action to the larger public. One of the STEW-MAP developers explained that by publishing this data and making it widely available, the map could lend legitimacy to these community efforts. They said:

"The idea to visualize this information in a platform that was common and shared by many people was really driven by the fact that we wanted to dispel some myths that were out there about community development and community action."

Target Knowledge Through Visioning Activities

In the case of Visionmaker NYC, the e-tool is designed to produce target knowledge through the creation of individual ecological "visions" for the landscape of New York City. Through this creation process, users are presented with various social-ecological trade-offs based on each decision they make. The users can then save their "visions" and view others' visions. The goal of this process is to shift people's perspective on urban nature in general. As one developer explained:

"They look at the [ecological] metrics and if you just paint one green roof on one building, it hardly moves the needle at all. And then people are like…oh. And they know how hard it is to get one green roof on one building right?"

However, the creators of the tool seemed surprised that, after observing people using the tool, users' targets were not reflecting a bold vision for NYC's ecology. After a workshop in Jamaica Bay, during which users generated very conservative ecological future visions for their neighborhood, one of the creators said:

"In the end we got like 82 visions out of it. And I forget the number but 78 or 79 of them kept the street grids and the street infrastructure all the same, you know they would paint green infrastructure on the side but, you know, parts of Jamaica Bay, it's going to have to go back to marsh."

Transformative Knowledge

The civic crowdfunding platform ioby has become an expert in the development and transmission of transformative knowledge. The impact of this e-tool goes far beyond the raising of monies, as it combines online resources with on-the-ground community organizing and coaching to ensure the owner of each proposed project is able to develop and share the target knowledge needed to successfully implement their idea. Their strategy is to connect users with people who know how to make change, such as city agencies, local experts, or people who have successfully implemented similar projects in the past. As an ioby employee explained:

"Knowing how decisions are made, knowing who to reach out to at your transit agency, knowing how to get a permit for something, that's all positive change that goes beyond fundraising that I think really contributes to a larger picture of folks being more civically engaged and thinking more about themselves as potential changemakers instead of just consumers of city services."

Furthermore, ioby works to collect and exchange transformative knowledge, particularly that which is related to processes of change, and make it available to a wider audience. This is evidenced by a library of resources and how-to guides available on the website as well as a series of webinars and other e-resources.

"We have them share what their steps were, what they learned along the way, some of the mistakes they made and we really try and summarize that into resources."

Other platforms do offer some information on *how* to steward. For example, the HTHC app provides instructional resources on pruning, tree planting, etc.

"The app is actually chock full of videos, documents, PowerPoint presentations, lots of information about threats to urban trees…and there's also a lot of information about how to properly steward a tree, we have videos on pruning, on how to steward, how to plant, so as I said, even if someone picks up the app and never uses it for its data functionality, it serves as a great learning tool."

As with target knowledge, many of the tool managers stated an aspiration that, through sharing system knowledge, users would develop transformative knowledge in the process.

Other tools such as Visionmaker NYC do not go as far as developing transformative knowledge. The e-tool asks users to envision what a future landscape of NYC could look like and understand the difference in ecological functioning between the current landscape and their vision but gives little in the way of then understanding the complex social, financial, and political forces at play in actualizing that vision.

DISCUSSION

Across the 6 e-tools, all of which focus on UGI management by stewards in New York City, we find evidence of all three types of knowledge being exchanged, with most interactions focused on the uptake of systems knowledge. Tool creators viewed systems knowledge as a precursor to target and transformative knowledge, suggesting familiarity with place and situation is needed before acting. The development of target knowledge was an aspiration for some tools, while others created intentional activities and platforms that allowed users to share their own targets and browse the vision of others. Finally, 2 tools engage with transformative knowledge by creating platforms to share information on how to make change. Below, these results are discussed and framed by the various processes of knowledge exchange.

Knowledge Brokering and Curation

Many of the e-tools serve as digital knowledge brokers by synthesizing knowledge from various sources to build a knowledge pool and making it more widely accessible. As Bodin et al. (2006) explain, brokers play the role of "translating" knowledge across networks and they are not just sharers of knowledge but also producers of a new kind of "brokered knowledge." Some of the cases act as passive knowledge brokers in that they synthesize knowledge from various groups and allow for users to create connections between themselves if they so desire. STEW-MAP allows users to search and find contact information for groups with whom they may want to connect. The NYC Street Tree map can also connect individual stewards to local organizations who are equipped with resources to support stewards. In this way, both maps are not directly making connections, but rather providing a directory of sorts that allows groups to connect across the network. ioby acts as a more "active" knowledge broker by matchmaking between knowledge holders and project leaders. ioby uses its online platform to broker and operationalize community-generated knowledge. In some of these cases, knowledge can be shared through both the use of the e-tool itself and by strengthening existing off-line networks. ioby, STEW-MAP, and the NYC Street Tree map are creating spaces for existing networks of stewards and community activists to network with and learn from one another.

One of the key functions of social-ecological memory is the perpetuation of continuity in an SES, which is a key factor for maintaining urban ecosystem health (Andersson and Barthel 2016). Many of the cases could be seen as assisting in maintaining ecosystem continuity through the collection and dissemination of data describing the social-ecological system. Visionmaker NYC, for example, allows users to see the historical landscape ecology of NYC while imagining their own ecological designs. The digitization and distribution of this historical data serve as one method of preserving knowledge of ecological functioning. Furthermore, the publicly stored collective visions of users can be seen as another format of knowledge now stored in a digital "cloud memory." E-tools have the potential to create new pathways for linking current and future land use to longer time frames and larger scales and processes through the documentation, digitization, and dissemination of social-ecological data. However, as Andersson and Barthel (2016) warn, "In the current time of fast change and easy access to 'knowledge,' some social networks of information and some types of ideologies often become dominant in highly politicized situations." Certainly, some of the e-tools have the potential to dominate other forms of knowledge such as local tacit or other scientific knowledge due to their highly accessible nature, and their utility as memory carriers should be further studied to avoid losing redundancy within the SES.

Knowledge Accessibility

A large amount of system knowledge is available to users on the e-tools, much of which could inform current or potential stewards of UGI. Digital tools have the advantage of hosting large amounts of complex data, often reflecting systems knowledge, and are accessible to many more people across space and time in comparison with more traditional "analog" forms of exchanging knowledge about social-ecological systems such as trainings, workshops, and peer-to-peer learning (Anderson 2008). This is of particular interest because stewards tend to be a fairly homogenous group in NYC (Fisher et al. 2010), which can lead to an inequitable distribution of UGI resources. Therefore, e-tools have the potential to share knowledge between people of more diverse demographic and socioeconomic statuses and drive more equitable distribution of UGI.

However, the complex and data-rich environments created by some of the e-tools may not encourage

effective knowledge exchange. For many of these tools, the usership can range from scientists to practitioners to first-time users. This has resulted in tools that are very data rich and highly complex, which can have implications on how knowledge is used for stewardship. In observing knowledge sharing in community gardens, Silva (2017) observed in their learning process that gardeners "seemed to experience an information overload, receiving much more codified explicit knowledge in the form of workshops and printed literature than they could readily apply, internalize, and make tacit in their practices." Silva concludes that study of more instrumental forms of learning in stewardship practice should be pursued in the future. Further studies evaluating usership and learning outcomes of e-tools from the perspective of the users could help advance understanding of the outcomes in the future.

In comparison to more mainstream tool development (i.e., private sector) that is often generously funded and responds to shifting market and user demand, there is a danger that e-tools developed by government and nonprofit institutions may be developed without a user or application in mind. Revisiting the information deficit model may explain the "if you build it, they will come" mentality of some of these tool developers who believe that presenting scientific data to the public will result in learning.

Knowledge Interpretation

Many of the e-tools found ways to overcome these high exploratory learning environments by presenting the complex data offered on the e-tool with in-person instruction or interpretation efforts. An emergent finding of the research was the success of place-based or in-person engagement practices in combination with digital knowledge-sharing strategies. These practices such as workshops, classroom curriculum, trainings, and place-based data collection were cited as successful strategies for effectively exchanging knowledge and eliciting participation.

The NYC Street Tree map and the HTHC app use a citizen science approach to collect the data used in the tool, meaning some users receive in-person instruction as an introduction to the tool. In both cases, formal training was held to introduce users to the resource and train them on how to collect data. In the case of Visionmaker NYC, a classroom curriculum was developed to allow middle school students to create ecological visions. Other e-tools such as

ioby and STEW-MAP allow knowledge holders to connect to interested parties and create a situation for effective in-person instruction. In these cases, the main goal of the tool is not to learn through using the tool itself but to access a network of knowledge. Both of these e-tools are essentially creating space for "offline communities to engage online" (Stiver et al. 2015), leveraging technology to enable and strengthen existing networks in communities.

This kind of hybrid learning approach may be a way forward for e-tools to exchange knowledge for meaningful stewardship action. By combining an online tool with in-person instruction and engagement, hybrid approaches allow for complex SES data to live online but in a format that is both accessible and digestible by stewards. These approaches offer a pathway for knowledge sharing and participation in a society in which technology is rapidly changing the way we relate to our surroundings. Further studies that examine tool users, learning outcomes, and place-based or hybrid approaches to e-learning are suggested.

Furthermore, the COVID-19 pandemic has forced many forms of social engagement to shift to become digital, making e-tools all the more relevant. This shift has shone a light on the rich world of learning and engagement that can happen entirely online. Some of the 6 cases investigated have developed new, virtual programming as a result of COVID-19, such as the HTHC app producing training videos in lieu of in-person programs and the STEW-MAP team interpreting a museum exhibition of their work to a virtual platform.

Future research could explore the experiences and outcomes of tool users, rather than just the developers, as was the focus of this study. Studying user experiences as related to the three knowledge types we examined could help elucidate which types of knowledge are most sought after by users and which are most effectively exchanged using digital platforms. Further study of the composition of usership of the e-tools as well as the beliefs and learning outcomes of the users would answer these questions and help to further describe the care dimension of stewardship. Furthermore, because technology develops very rapidly, this study is only able to represent a snapshot in time, and documenting the changing landscape of e-tools and digital learning environments will add context to this emerging field. Finally, the link between knowledge sharing and stewardship action needs to be further examined, particularly with an

emphasis on digital learning as these tools and methods increase in prevalence.

CONCLUSION

The findings of this study identify how e-tools for UGI management by stewards are designed: to share data about social-ecological systems and to create spaces for citizen-government interaction and peer-to-peer learning. We find most e-tools we studied focus on systems knowledge, with some tools addressing target and transformational knowledge. We find several examples of on-the-ground and in-person practices that, paired with the e-tools, produced positive learning outcomes. E-tools are serving as platforms that broker knowledge between silos and make this knowledge more accessible to users. This suggests that special attention should be paid to the instruction offered through these tools. This finding suggests that exploring only knowledge exchange vis-à-vis digitized tools gives an incomplete picture. A hybrid approach to instruction that harnesses the power of digitization but incorporates place-based, embodied knowledge sharing may offer a way forward and merits future investigation. Combining large-scale data on digital platforms with other forms of knowledge exchange in this hybrid framework will allow for the development of tacit knowledge and deepen social ties, which can strengthen the outcomes for civic stewardship.

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Résumé. Contexte: Les individus qui s'occupent des infrastructures vertes en ville, notamment les arbres urbains, jouent un rôle important dans le maintien de la qualité de l'environnement urbain. Mais que se passe-t-il lorsque le traitement de l'information et la génération de connaissances se numérisent ? Cette recherche examine les outils numériques développés pour fournir un soutien à la connaissance tout en ayant pour ambition d'inciter à l'intendance. Il s'agit de savoir sur quelle compréhension ils s'appuient, quelles informations ils transmettent et comment ils abordent la prise en charge et l'utilisation du contenu qu'ils fournissent. Méthodes: Nous avons analysé 6 outils numériques distincts dans le contexte de l'infrastructure verte urbaine de la ville de New York, New York, USA. Nous avons mené des entrevues semi-structurées avec les développeurs des outils et évalué les outils numériques eux-mêmes. Résultats: Nos résultats indiquent que la plupart des outils numériques sont conçus pour donner accès à différents types d'informations sur les systèmes socio-écologiques urbains afin, de manière passive ou plus active, de stimuler l'apprentissage. Au-delà des conditions d'apprentissage numériques riches, complexes et exploratoires, de nombreux outils combinent des expériences virtuelles avec des formations, des ateliers et un accompagnement en personne. Conclusion: Les approches hybrides observées exploitent le pouvoir des plateformes numériques afin de permettre une utilisation diversifiée ainsi que le partage de vastes quantités de données tout en recourant à des techniques d'organisation plus traditionnelles sur le terrain et offrant de ce fait, une marche à suivre à une époque où les données numériques deviennent prépondérantes. Les prochaines recherches sur l'utilisation des outils numériques, les approches d'apprentissage hybride et les liens avec les résultats de l'intendance pourraient enrichir la compréhension du fonctionnement des outils numériques ainsi que leur potentiel et leur impact socio-écologique.

Zusammenfassung. Hintergrund: Die Pflege der städtischen grünen Infrastruktur, nicht zuletzt der Stadtbäume, spielt eine wichtige Rolle für die Erhaltung der Qualität der städtischen Umwelt. Aber was passiert, wenn Informationsverarbeitung und Wissensgenerierung digitalisiert werden? In dieser Studie werden digitale Werkzeuge untersucht, die entwickelt wurden, um Wissen zu vermitteln und zur Pflege anzuregen. Sie geht der Frage nach, auf welches Verständnis sie zurückgreifen, welche Informationen sie vermitteln und wie sie die Aufnahme und Nutzung der von ihnen bereitgestellten Inhalte angehen. Methoden: Wir analysierten 6 verschiedene E-Tools im Kontext der städtischen grünen Infrastruktur in New York City (NY, USA). Wir führten halbstrukturierte Interviews mit den Entwicklern der Tools und bewerteten die E-Tools selbst. Ergebnisse: Unsere Ergebnisse zeigen, dass die meisten E-Tools so konzipiert sind, dass sie Zugang zu verschiedenen Arten von Informationen über städtische sozial-ökologische Systeme bieten und passiv oder aktiv zum Lernen anregen. Zusätzlich zu reichhaltigen, komplexen, explorativen digitalen Lernumgebungen kombinieren viele Tools virtuelle Erfahrungen mit persönlichem Training, Workshops und Coaching. Schlussfolgerung: Die beobachteten hybriden Ansätze machen sich die Möglichkeiten digitaler Plattformen zunutze, um eine vielfältige Nutzung und den Austausch großer Datenmengen zu ermöglichen, während gleichzeitig traditionellere Organisationstechniken vor Ort zum Einsatz kommen. Sie bieten somit einen Weg in die Zukunft in einem Zeitalter der zunehmenden Dominanz digitaler Daten. Zukünftige Forschungen über die Nutzung von E-Tools, hybride Lernansätze und die Verbindungen zu den Ergebnissen des Stewardship könnten das Verständnis für die Funktionsweise von E-Tools sowie ihr sozial-ökologisches Potenzial und ihre Auswirkungen bereichern.

Resumen. Antecedentes: Las personas que cuidan la infraestructura verde urbana, en particular los árboles urbanos, desempeñan un papel importante en el mantenimiento de la calidad del entorno urbano. Pero ¿qué sucede cuando el procesamiento de la información y la generación de conocimiento se digitalizan? Este estudio examina las herramientas digitales desarrolladas para proporcionar apoyo al conocimiento y con ambiciones de incitar a la administración. Se pregunta en qué comprensión se basan, qué información negocian y cómo abordan la aceptación y el uso del contenido que proporcionan. Métodos: Se analizaron 6 herramientas electrónicas diferentes en el contexto de la infraestructura verde urbana en la ciudad de Nueva York, Nueva York, EE. UU. Realizamos entrevistas semiestructuradas con los creadores de herramientas y evaluamos las herramientas electrónicas en sí. Resultados: Nuestros hallazgos indican que la mayoría de las herramientas electrónicas están diseñadas para proporcionar acceso a diferentes tipos de información sobre los sistemas socioecológicos urbanos y, de forma pasiva o más activa, estimular el aprendizaje. Además de los entornos de aprendizaje digital ricos, complejos y exploratorios, muchas herramientas combinan experiencias virtuales con capacitación en persona, talleres y asesoría. Conclusión: Los enfoques híbridos observados aprovechan el poder de las plataformas digitales para permitir la diversidad de usuarios y compartir grandes cantidades de datos al tiempo que emplean técnicas de organización sobre el terreno más tradicionales y, por lo tanto, ofrecen un camino a seguir en una era de creciente dominio de los datos digitales. La investigación futura sobre el uso de herramientas electrónicas, los enfoques de aprendizaje híbrido y las conexiones con los resultados de la administración podrían enriquecer la comprensión de cómo funcionan las herramientas electrónicas, así como su potencial e impacto socioecológico.