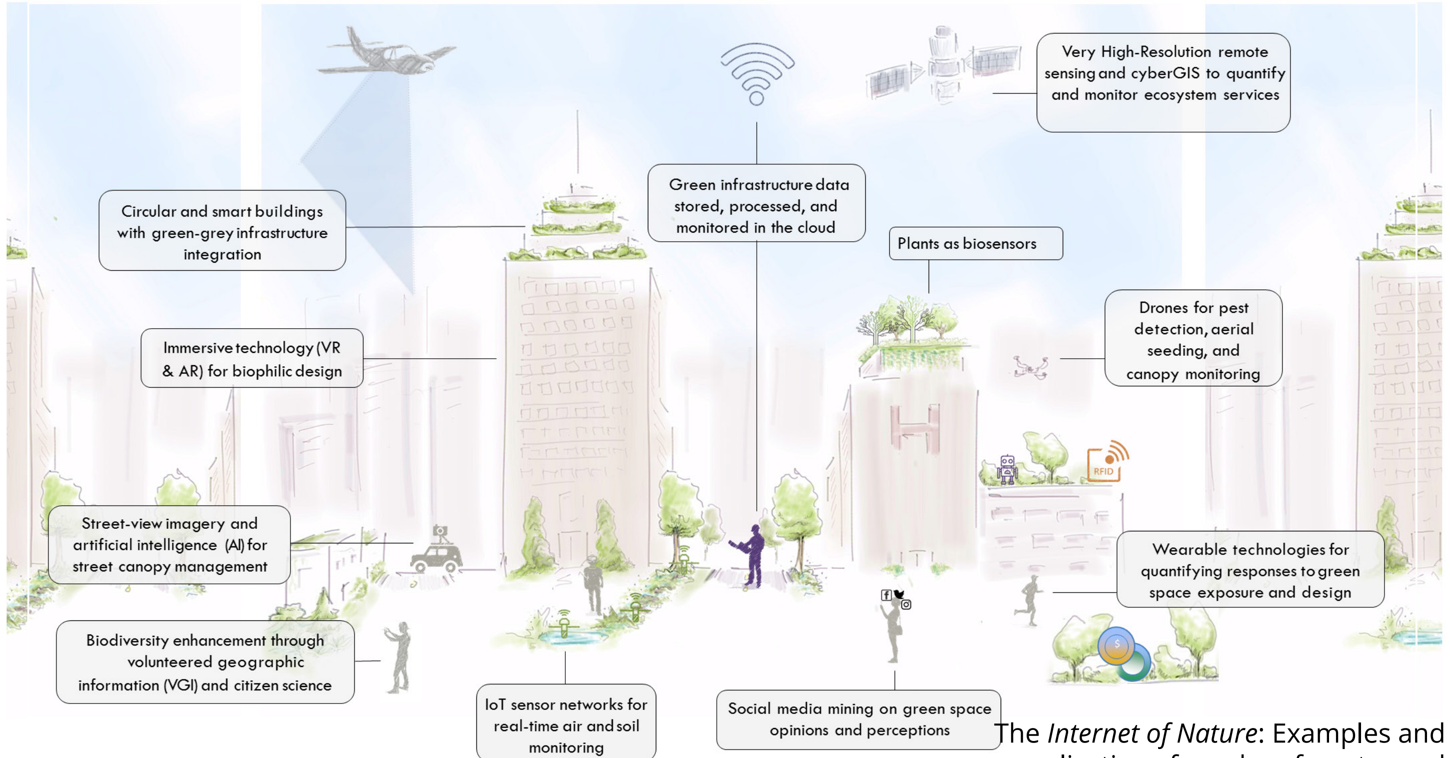

The *Internet of Nature*: Examples and applications for urban forestry and green infrastructure management. From The Internet of Nature

Biophilic Cities for the 22nd Century

By Nadina Galle and Sophie Nitoslawski

Take nature online. It might sound crazy, but plugging nature into a city's existing (and growing) digital infrastructure—where urban ecosystems can be described and represented through technology—might be exactly what the world needs to build the biophilic cities of the future.

Introduction

We are living in an era of unprecedented growth in cities—the future is decidedly urban. Never before have so many people lived in cities, and of such great magnitude. The United Nations now predicts that the world will have 43 megacities (over 10 million people) by 2030. Three million people are not just moving to cities every single week—they are staying there for the rest of their lives. These days, the entire life-cycle of human beings takes place in cities. In stark contrast to the savannas in which we evolved, the urban landscape is becoming the default biotope for humankind.

Urbanization at this scale requires a broad and systemic redesign. Nature is already illustrating how extreme and novel cities (or "urban ecosystems") have become, mostly through the phenomenon of "urban evolution". Urbanization, defined as the alteration of natural habitat into a landscape primarily consisting of gray infrastructure such as buildings, roads, and other human-engineered amenities, results in other abiotic changes, such as increased pollution, altered light patterns due to artificial light production, growing impervious surface area, and the introduction of "human" foods and waste.

Urban animals and plants are evolving accordingly. In *Darwin Comes to Town: How the Urban Jungle Drives Evolution*, Dr. Menno Schilthuizen aptly describes how pigeons develop detox-plumage to protect against lower air quality, while blackbirds sing at a higher pitch to ensure detection over noisy traffic (Nemeth & Brumm 2009). Weeds growing out of cracks in the pavement produce heavy, compact seeds designed to drop close to the plant and promote reproduction, a change which evolved over a period of just 12 years (Cheptou et al. 2008). Evolution at this temporal scale is in stark contrast to the Darwinian notion that evolution could never be seen in a single lifetime. Schilthuizen (2018) proves that these organisms are on their way to becoming entirely novel, and very urban, species. These examples illustrate the now extreme conditions of city environments, and the complexities involved when working with nature in an urban age.

Urban Nature's Benefits and Services

Interest in biophilic cities has reached a turning point, and rightly so. Many urban dwellers are sweltering under extreme heat events, suffocating due to poor air quality, and buckling under immense mental stress that may in part be attributed to the urban environment. People in cities spend as much as 90% of their lives indoors, and when people do go outside, it typically occurs within urban areas (Custovic, Taggart & Woodcock 1994; Hoppe & Martinac 1998). More and more, the urban nature and green infrastructure in cities is being called upon to play a crucial role in climate change adaptation and mitigation. Studies highlight the contributions of urban nature to all facets of urban life. Also known as ecosystem services (ES), these benefits enhance quality of life and contribute to human well-being. Now a commonly-understood term in urban ecology, ES provides "a

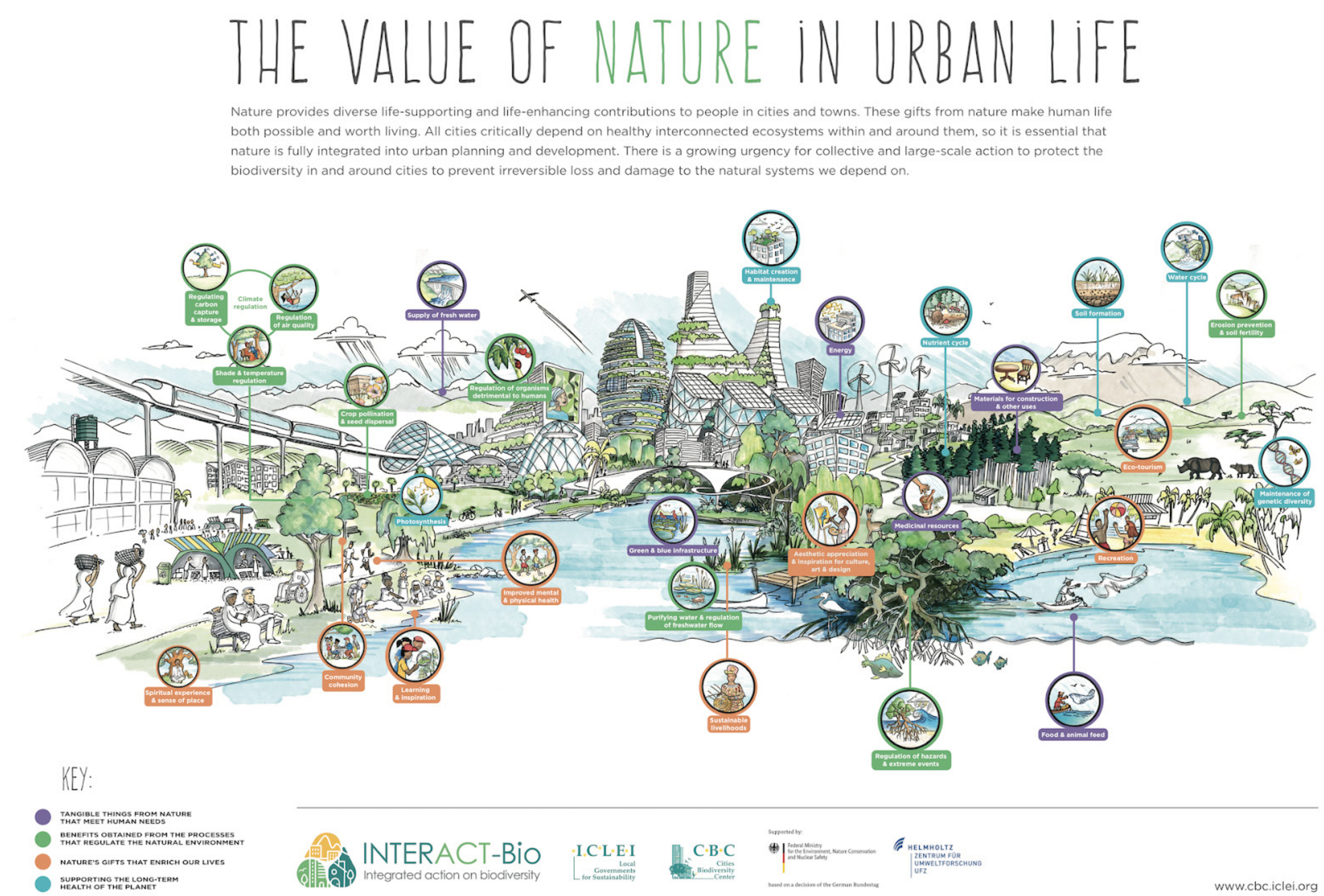

Figure: Nature provides many diverse life-supporting and life-enhancing contributions to people in cities and their surrounding regions (ICLEI, 2018).

The Value of Nature in Urban Life poster was produced as a part of the INTERACT-Bio project. INTERACT-Bio is implemented by ICLEI - Local Governments for Sustainability and supported by the German Federal Ministry for the Environment, Nature Conservation and Nuclear Safety (BMU) through the International Climate Initiative (IKI).

framework for conceptualizing and managing human–environmental interactions" (Daily et al. 2009), elevating the importance of urban nature in urban sustainability discourses.

Urban nature provides a suite of ES and co-benefits compared to more traditional gray infrastructure (Duinker et al. 2015). Broadly speaking, the ecological benefits of urban nature relate to wildlife habitat, biodiversity protection and conservation, improved water and air quality, stormwater management, cooling and shade provisioning, and carbon storage. From an economic perspective, trees promote local economic activity and development and, in some cases, increase property values and contribute to energy savings. At the societal and cultural level, urban green infrastructure contributes to general well-being, promotes tourism and recreational activities, provides educational opportunities, and can enhance community safety. Urban nature is increasingly recognized as an important social determinant of health, with the potential to restore and positively contribute to mental health. Trees in particular are a vital component of urban green infrastructure; they are special and unique in that "they predominate in contributing to the vertical dimension of the plant community on account of their height," playing a significant role in heightening the visual experience of urban dwellers (Duinker et al. 2015, p. 7380).

Unfortunately, ecosystem services are not necessarily evenly distributed across cities. Issues of green equity have gained prominence in urban planning, as some research shows that neighborhoods associated with lower socio-economic outcomes have reduced access to high-quality green spaces (Nesbitt et al. 2019). Lower-income and marginalized communities are often disproportionately impacted by climate-related events, which can be mitigated through tree canopy enhancement. More recent research has elucidated relationships between maternal exposure to green space and infant birth weight (Cusack et al. 2018), highlighting the long-term significance of working towards accessible and equitable delivery of green benefits.

Furthermore, many urban forests and associated green spaces are frequently degraded due to lack of resources and capacity for maintenance, conflicts with gray infrastructure, and abiotic stresses common to urban environments. Soil compaction, urban heat islands, overhead utility wires, communication and gas lines, construction and demand for housing, election cycles, and budget allocation prove challenging to varying degrees when managing urban green infrastructure. The lack of consistent, reliable, and precise data on urban forests and green spaces is also a common theme across municipalities, hindering proactive decision-making. The piloting and implementation of novel practices for monitoring green infrastructure are thus sorely needed to unearth uniquely urban interactions, and improve the delivery of ecosystem services that benefit the lives of urban dwellers everywhere.

The Internet of Nature (IoN)

Enter the "Internet of Nature" (IoN): a new approach to urban ecosystem management where individual parts of an ecosystem can be described and represented through digital technologies and applications, allowing us to unearth synergies between components and enhance resilience in urban ecosystems (Galle et al. 2019).

In a forest, trees "talk" via mycorrhizal fungi that colonize the plant's root system and develop a symbiotic association called "mycorrhiza" (from the Greek mukés, meaning fungus, and rhiza, meaning roots) (Das 2015). These fungi have existed since the first plants appeared on dry land more than 450 million years ago. Mycorrhizae work by forming a network of very tiny, almost microscopic, threads called "hyphae." These networks allow for biological communication, in which nutrients, water, CO2, and even information (e.g. defense signals about pests and disease) are exchanged.

These microbes are essential for healthy soil, and in turn, a healthy urban ecosystem. However, these fungal networks which have kept forests and plant systems self-regulating and self-sufficient for hundreds of millions of years are highly fragmented in cities. There is compelling evidence showing urban trees struggle compared to their rural counterparts. Bainard, Klironomos & Gordon (2011) found urban environments have lower microbial activity and diversity compared to rural or natural ecosystems, while Roman & Scatena (2011) found urban forestry literature frequently reports high mortality rates and low average lifespans for street trees.

With the increasing recognition that green and naturalized spaces are crucial to urban design, coupled with the rapid and widespread utilization of data and digital technologies for municipal decision-making, what if technology could step in where Earth's biological communication networks have been altered and disrupted? The IoN, or a city's bio-technological communication network, could be the innovative approach needed to better value, understand, and manage these novel ecosystems.

Applying the IoN, Across the World

From sensor networks for real-time soil monitoring, to mining social media for public opinion on green spaces, to drones for pest detection, to remote sensing for ecosystem services analysis, the IoN can be applied in several different ways. The idea is to digitally represent aspects of urban nature, and connect it to wider city communication networks and systems. When several of these pieces act in unison, we are able to collect "ecosystem intelligence," where information and data obtained

The Internet of Nature is where urban ecosystem components and interrelation dynamics are described and represented through digital technologies and applications. These may include, but are not limited to, information and communications technology (ICT), remote sensing, machine learning, sensors and data loggers, 5G communications and advanced computing. In this representation, the benefits of urban nature are enhanced and self-organization, self-regulation, and automation can be achieved.

Ecosystem Intelligence refers to information and data obtained from the digital representation of these urban ecosystems, which can be used to inform management and planning decisions. The ultimate goal of elucidating ecosystem intelligence is to understand the "language" or urban ecosystem elements, and determine how ecosystem components interact in a city's social-ecological landscape.

Urban Nature		**Urban Technol-**	
Green Infrastructure	The collection of natural vegetation, soils, and bioengineered solutions that collectively provide society with a broad array of products and services for healthy living.	Augmented Reality (AR) and Virtual Reality (VR)	VR is a complete immersive experience meant to simulate real or fantasy-based environments. AR is where the real environment is enhanced with computer-generated, virtual objects, often for visualization purposes.
Ecosystem Services	The suite of benefits that humans freely gain from natural and semi-natural environments, especially from functioning ecosystems.	Artificial Intelligence	The simulation of human intelligence processes by computer systems, in order to perform tasks (e.g. decision-making) normally requiring human intelligence.
Urban Forests	A specific type of green infrastructure, defined as all woody and associated vegetation found in an urban setting.	Big Data	Extremely large data sets that may be analyzed to reveal patterns, trends, and associations, and that are often too complex to be dealt with using traditional methods.
		Internet of Things (IoT)	The extension of the internet to a range of objects, processes, and environments.

from the digital representation of these urban ecosystems can be used to inform management and planning decisions. The ultimate goal of elucidating ecosystem intelligence is to understand the "language" of urban ecosystem elements, and determine how these interact in the urban landscape. This is critical when large amounts of data are needed to model and predict urban stresses and impacts. For the purposes of this article, we look at how the IoN, and by extension, emerging technologies, can actually bring people closer to the goal of biophilic cities. Biophilic (from bio-, referring to "life", and philia, meaning "love") cities are not, by definition, anti-technology. In fact, the IoN does not serve to replicate the natural world with technology at all, but rather to utilize technology to improve urban environmental management. This article explores how the emerging technologies put forward by the IoN hold the potential to revolutionize urban ecology. We draw on four global case studies to understand how the IoN is being applied, right now.

Immersive Technology for Biophilic Design

By Ash Welch, AECOM

Biophilic cities and design are intricately interconnected. If biophilic cities describe places where people have an innate love for, attachment to, and even need for nature, then biophilic design must necessarily promote connection to the natural environment. We asked senior Green Infrastructure & Biodiversity Specialist at AECOM, Ash Welch, to illustrate how immersive technology can play a role in biophilic design.

Immersive technology, such as virtual reality (VR) and augmented reality (AR), is steadily becoming commonplace within mainstream applications. While its entertainment uses are obvious, there are also opportunities to deploy this technology to aid green infrastructure design – for example, using 3D illustrations and VR to create realistic-looking models. By making it easier to see how design changes will look, this approach can improve collaboration and efficient working between engineers, ecologists and other disciplines. This was particularly pertinent for AECOM in designing a biodiverse rooftop terrace for Adastra House in London, in which VR was used to complement solar photovoltaics and greenery but also to encourage the client to fully implement AECOM's habitat recommendations (Figure 2).

Visualizing and experiencing green infrastructure design is a powerful method of communication. It allows clients, stakeholders and the general public to experience a biophilic landscape design's true dimensions and aesthetics with a sense of perspective, which is otherwise impossible until the landscape is built, planted and mature. VR and AR models can also be created with varying levels of animation, interactivity and soundscapes to create an accurate impression of a biophilic development or landscape.

Figure 2: The Adastra House, a biophilic rooftop terrace on a residential apartment block in North London.

For example, AECOM created 3D models and animations as part of a feasibility study for a green footbridge. These models can then be integrated into VR applications to enable users to fully experience how the concept would seamlessly integrate into the surrounding landscape (Figure 3). Using immersive technology to benefit urban habitat design is still very much in its infancy. However, its value in engaging stakeholders and the general public with the consultation process is clear, particularly as research shows VR can make people more sympathetic towards causes (Ahn et al. 2014).

Figure 3: A38 Green footbridge feasibility study concept design for Highways England.

Very High Resolution Remote Sensing for Urban Tree Inventories

Evidence continues to show that urban forests and other green spaces are paramount to urban liveability. However, monitoring and management of these socio-ecological systems continues to challenge many municipalities, particularly those constrained by lack of resources and capacity. Tree inventories are a start to making sense of urban forest complexity by itemizing the species, size, age, location, and condition of trees. Inventories produce crucial information on the health and diversity of the urban forest, and are a necessity for effective planning.

Tree inventories are, for the most part, completed via manual field surveying, where an arborist will use a checklist or mobile app-based software to record key metrics on each tree. Surveying has its fair share of disadvantages: it's expensive to conduct, laborious to update regularly, and based on observation-based estimations, leading to errors and concerns about data quality (Roman et al. 2017). Furthermore, many tree inventories are incomplete as they only include publicly-owned trees, when in many cities, over half of the trees are on private lands (Jacobs, Mikhailovich & Delaney 2014; Nowak & Greenfield 2012). Despite being on private land, these trees still offer significant community benefits, and cities have an increasingly vested interest in tracking their status.

Very high resolution (VHR) satellite imagery can help. Ever since the 1972 launch of the Earth Resources Technology Satellite (Landsat 1), remote sensing has been increasingly applied to monitor Earth's ecosystems. With the technological improvements of satellite sensors and machine learning algorithms, we have reached a new application epoch of Earth observation.

Green City Watch, a geospatial artificial intelligence (geoAI) firm specialized in urban ecological engineering, is developing TreeTect™, which inventories all public and private urban trees in a given city, and monitors these in near real-time (Figure 4). TreeTect™ utilizes satellite imagery, computer vision, and machine learning to pinpoint individual tree species, size, location, and condition. The growing space conflicts of the tree can then be estimated. In practice, an inventory like this could mitigate liabilities by continuously tracking tree condition and maintenance needs, justify budgets by visualizing impact of underfunded and reactive planting, maintenance and removal protocols, and enhance urban forests by identifying illegal tree removal and locating vacant planting areas. All in all, TreeTect™ can help minimize labor-intensive, expensive field surveying—offering a novel application to enhance efficiency and decision making in urban forestry.

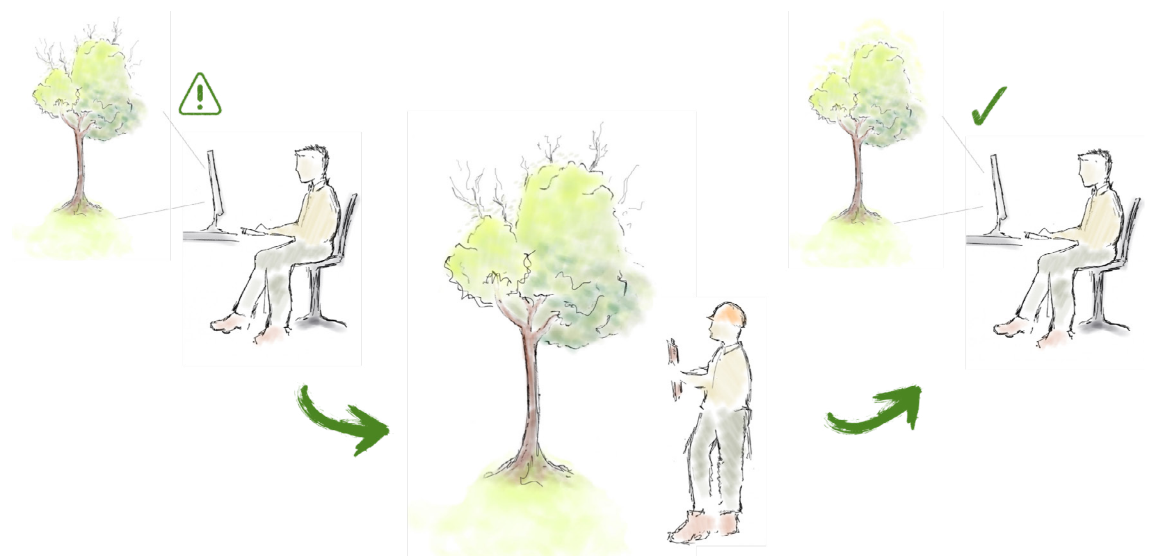

Figure 4: TreeTect™ by Green City Watch, offers city arborists and planners a smarter way to identify, map, and track one of their most important assets: trees.

Google Street View to Quantify the Street Canopy

By Carlo Ratti and Fábio Duarte, MIT Senseable City Lab

What might biophilic cities look like from the street? Carlo Ratti and Fabio Duarte, director and research scientist of the Senseable City Lab at the Massachusetts Institute of Technology (MIT), respectively, explain that using data-driven technologies to better understand urban nature holds massive potential.

Since Google Street View (GSV) was launched in 2007, its cars have been collecting millions of photographs in hundreds of cities around the world. In New York City (USA) alone, there are about 100,000 sampling points, with six photographs captured in each of them, totaling 600,000 images. In London (UK), this number reaches 1 million images. The GSV fleet now also includes bicycles, trolleys (for indoor spaces), snowmobiles, and "trekkers" (for areas inaccessible by other modes). Such an overwhelming abundance of images becomes increasingly interesting when we consider them as a rich source of urban information.

At the Massachusetts Institute of Technology (MIT) Senseable City Lab, using large GSV datasets composed of hundreds of thousands of images per city, Li et al. (2015) and Seiferling et al. (2017) calculated the percentage of green vegetation in streets, using computer vision techniques to detect green pixels in each image and subtract geometric shapes (Figure 5).

With a few computational steps, what is left from this subtraction is greenery. Since the GSV data acquisition procedure is standard, these methods enable the calculation of street greenery in dozens of cities around the world and to compare them—using what they call the "Green View Index".

Using computer vision and machine learning techniques to analyze 'big data' datasets of GSV images helped to understand urban features in ways that would take too long or be financially prohibitive for most cities using human-based or other technological methods. By using GSV data with computer vision techniques, MIT Senseable City Lab demonstrated the value of bringing 'big data' to the human level, to the tangible aspects of urban life.

IoT Sensors for Soil Health

By Didy Arnold, Treemania

Compaction, construction, and pollution—urban soils face a myriad of anthropogenic pressures. The role of soil, along with biological and microbial activity, is relatively understudied in urban forest landscapes (Herrmann et al. 2018). Biologist and Co-Founder of Treemania, Didy Arnold, tells us how technology and IoT can help monitor interactions between urban trees and soil.

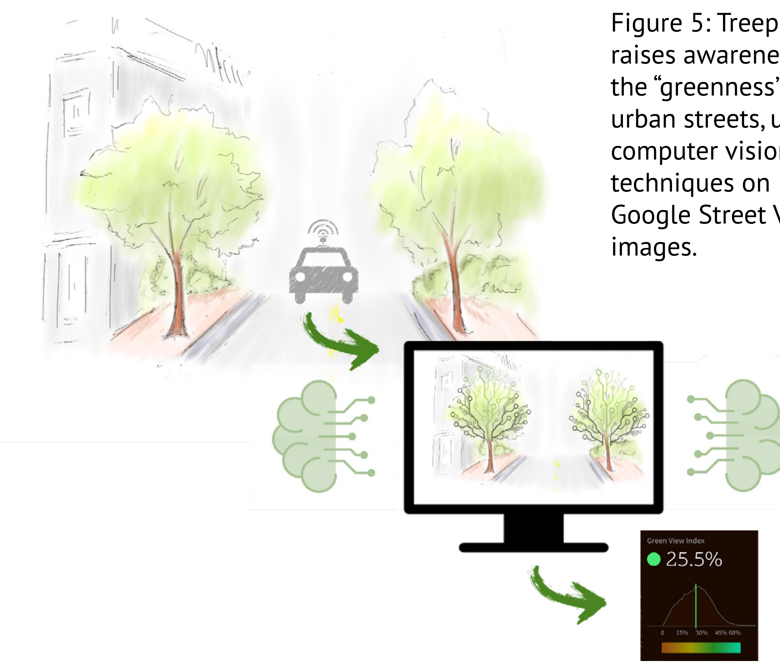

Figure 5: Treepedia raises awareness on the "greenness" of urban streets, using computer vision techniques on Google Street View images.

Treemania is a Dutch startup that focuses on greening cities and making agriculture more sustainable. Aboveground, Treemania engineers ideal growing conditions using a combination of plants that act as natural enemies for the most common pests and diseases for planted trees. By planting a diversity of tree species, the chance of infection greatly diminishes. When choosing tree Diversity of tree species, the chance of infection greatly diminishes. When choosing tree species and finalizing designs, ecosystem services such as stormwater regulation, shade and cooling, carbon sequestration and storage, and air quality improvements are taken into account.

Achieving a healthy soil filled with organisms, both large and small, forms the basis for all of Treemania's projects. Urban trees are detached from one another in such a way that it prevents mutual root contact and hinders fungi and bacteria symbiosis. To monitor the developments in the soil and to be sure that newly planted trees have sufficient moisture and nutrients at their disposal, Treemania uses sensors. With sensors, soil moisture is measured in real-time, as this is essential for both the tree and the life in the soil.

At quick glance, on their dashboard, tree care providers can now see how much water newly planted trees need to thrive. New trees and shrubs need regular and consistent watering until root systems establish. Lack of establishment due to lack of water is the most common reason for failure in the first three years of planting. By measuring soil electrical conductivity (EC), or the amount of salts in soil (salinity of soil), trees can be saved from salinized soils due to run-off road salt. Treemania has also developed a sensor to monitor whether the environment in the root zone is favorable for the development of the correct organisms that feed the plants and convert organic material into the soil. If necessary, improvement measures can be implemented based on this data, keeping trees healthy and mitigating vulnerability to pests and disease.

Treemania's dashboard can also engage citizens and involve residents in "their" neighborhood greenery. For example, the residents of Geijsteren, a small village in the east of the Netherlands, can follow the condition of "their" Linden trees on a screen in the local cafe. When the trees are thirsty, the residents can take action and follow the progress on the screen, together.

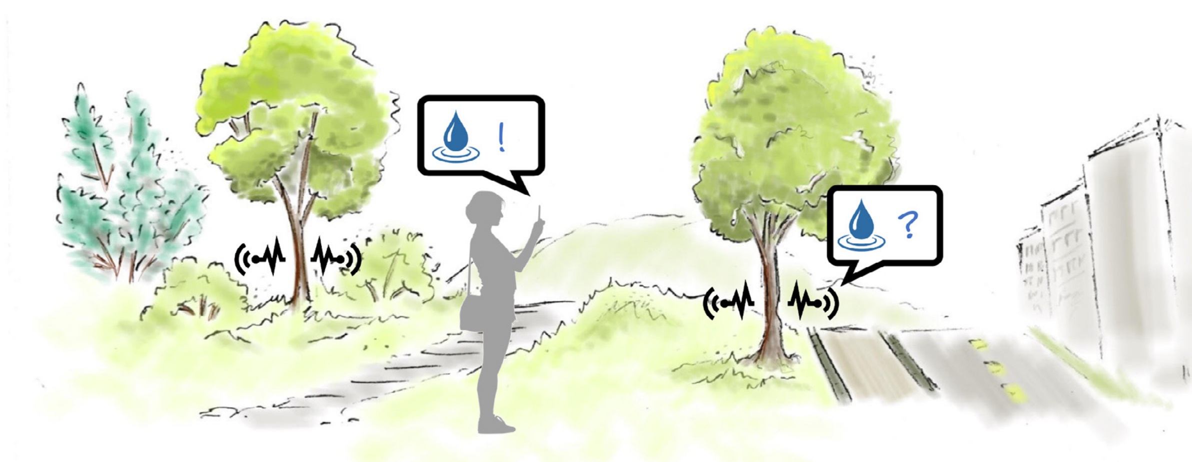

Figure 6: Treemania raises the alarm when soil is facing water shortage and other life-threatening conditions for trees.

Conclusion

In an increasingly digital society, intersections between urban nature and technology will become more prominent. The urban challenges that we face, such as pollution, climate-related events, population growth and immigration, and economic and social inequalities, call for innovative approaches to valuing and managing our urban natural capital. As nations urbanize and as cities grow, we need to ensure that practitioners have the resources to make proactive and informed decisions about trees and green spaces, to provide green benefits that are accessible and shared by all.

Whether the IoN is applied to directly improve people's relationships with nature, or better the quality of urban nature for people to enjoy and benefit from, technology can play an important role in designing, managing, and connecting our urban green spaces. With this in mind, the gathering of ecosystem intelligence will require standardized and transparent data stewardship. Moving forward, it will be essential to ensure that applications of the IoN promote accessibility and transparency, without compromising citizen and municipal rights. Ultimately, the IoN should offer a newfound ability to understand and respond to the needs of urban ecosystems—to monitor and manage, enhance ecosystem function and resilience, and link the complex social and ecological systems that make up our cities.

Nadina Galle is a PhD candidate in Ecological Engineering jointly at UCD Spatial Dynamics Lab, MIT Senseable City Lab, and Trinity College Dublin; CEO and Co-Founder of Green City Watch, an award-winning geoAI platform for the real-time monitoring of urban nature; and Innovation Director at the Internet of Nature.

Sophie Nitoslawski is a PhD student in Urban Forestry at the University of British Columbia, Green College Sustainable Development Fellow, and Research Director at the Internet of Nature.

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