Green waste to green architecture: optimizing urban tree systems for renewable construction material supply chains.

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Abstract
In this article, we share the prospect of using the lifecycle and growth advantages of urban trees as construction materials beyond the existing, more typical green infrastructure uses. Much work has been completed on green infrastructure, but the potential tie to the material and construction industry is underdeveloped. It is this symbiosis between our environmental green infrastructure systems, natural and designed and our social systems; the decision-making, design, materiality and fabrication of our built environment in more sustainable directions which is the goal of this research. Technological advances now allow urban wastes from tree maintenance (e.g. pruned boughs and branches) to be locally processed as viable construction materials in new ways and forms. If these are optimized in coordination with other environmental and social systems and efforts, we will see functional and environmental improvements in our urban environments with reductions in both imported materials and exported wastes and improved energy levels and carbon sequestering.

Key words: circular economy, multiscalar modeling, socio-environmental systems, sustainability, waste to resources.

1. Toward a more systems-based sustainability

The negative impacts of human development on the environment are becoming more apparent and acute as time passes. Upstream consumption and downstream wastes of urban metabolisms (Derible et al, 2021, pp 85-114; Barles 2010, pp 439-455) has grown to unpresented proportions. Efforts toward green infrastructure and green buildings are seen as solutions to some of the direct and indirect emissions that contribute to environmental challenges relating to climate change, Urban Heat Island Effect (UHI) and other anthropocentric issues. However, in order to tackle our issues in the scale or time-frame needed, greater optimization is needed to reduce the impact. Realizing the complexity of our challenges and that all our issues, systems and realities are interconnected is part of the solution. The more we can connect systems and have them work together rather than separately is key to finding more comprehensive sustainable solutions. One opportunity for further enhancement through this systems approach to sustainability is pairing urban forestry systems with building material systems.

1.1 Urban trees and green waste

Urban trees are living things which grow and change and bring a myriad of benefits to us, our cities and biodiversity, but require water use and regular care and maintenance for various social purposes, resulting in wastes. Tree care within our cities and towns includes the removal of boughs and branches for the sake of safety, accessibility and aesthetics revolving around a variety of social purposes. This biomass is a type of green waste consisting of organic material that is considered clean with the ability to break down naturally in the environment. Some of these wastes are important for soil and tree system health, however, much of the material is cleared and gathered resulting in problematic concentrations. According to the EPA, landscape trimmings have consistently accounted for over 12% of Municipal Solid Waste for several decades. In more progressive states and cities green waste is now recycled rather than adding it to landfills, but tends to end up as compost, rather than being sorted into potential building materials. In 2022 California enacted new green waste legislation as organic waste makes up half of what they dump in landfills and that in part due to the methane release the reduction will have a rapid impact on the climate crisis.

There has been some exploration of reusing green waste from urban trees, for example, compost, chips, firewood, and pallets (Lan, Zhang and Yao, 2022, p 944). The study conducted by Lan et al. concluded that "the most environmentally beneficial combination is using merchantable logs for lumber and residues for biochar" (p 944). In practice, there emerged some firms and organizations acquiring urban trees for timber. For example, the Urban Wood Project in multiple cities in the United States (e.g., New York, Baltimore, Detroit) has been building furniture with reclaimed wood including urban trees removed for disease, maintenance or storm damage (The Urban Wood Project, 2023). Other cases include the Community Woodworks in Oakland, California, the Willard Brothers Woodcutters, in Trenton, New Jersey, and WoodWins, in St. Paul, Minnesota (USDA, 2022, p 4).

1.2 Opportunities for building materials

In the construction industry, wood is currently the only renewable resource for building, but is generally harvested and processed remotely and transported over long distances. Transportation distance has a significant effect on the energy and CO_2 impact of wood construction activity and can be reduced with local sourcing (Gustavsson & Sathr, 2006, p 949). Reducing our dependence on transported construction materials will aid in reducing congestion and the amount of carbon emitted relating to both the building and transportation industries.

1.3 Alignment between waste resources and material needs

We ask, can underutilized local natural infrastructures like urban tree waste be upcycled into construction materials for serving the wood needs in urban areas? In doing so, it will also reduce the needs of long-distance transportation. What optimizations can be made between environmental services of tree distributions and demands of building development and construction? Our thesis is that technological advances now allow urban wastes, such as green waste from tree maintenance, to be locally processed as viable construction materials. We anticipate that if urban tree maintenance is optimized in coordination with construction and other environmental and social systems and efforts, we will see functional improvements in urban environments with better planning and care toward greater water and energy savings as well as reductions in both imported materials and exported wastes (See Figure 1).

Documenting urban trees at multiple scales over time with various digital and analog methodologies will enable us to quantify the amount of resource potential entering our waste streams in the maintenance processes. We can then align with tree planting initiatives and other programs to simulate more strategic implementation of this infrastructure and connect with communities and other user groups to decrease our dependence on out-sourced materials and labor, while beautifying our built environment and helping the UHI and other environmental impacts. Apart from the pressing need for symbiotic interdisciplinarity in urban inputs and outputs, it is this connection across scales, from the micro of the material to the macro of the urban environment which is also a needed sustainable direction. However, most regional scale design foci do not get to the level of material and vice versa.

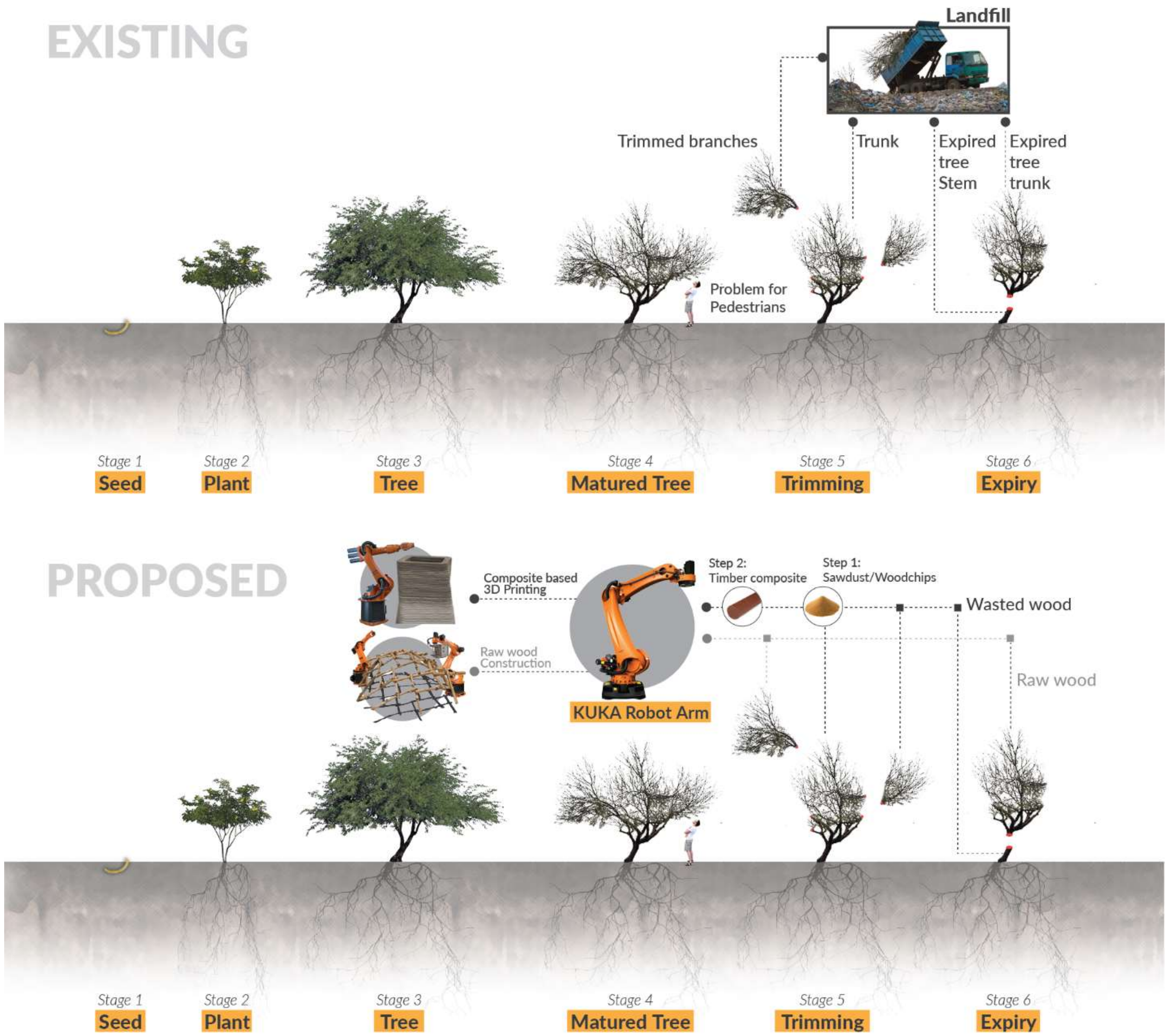

Figure 1 Diagram showing existing vs proposed use of urban tree green waste

At the same time, the design of our built environment has historically been the realm of the construction, planning and building industries. There is a pressing need to start researching our building materials across multiple scales, understanding the networks and flows of the connections in order to engage broader more sustainable research on the reshaping of our built environment (Ibanez, et al., 2019). We argue for synergizing social-environmental systems to connect urban tree development with sustainable building materials (See Figure 2).

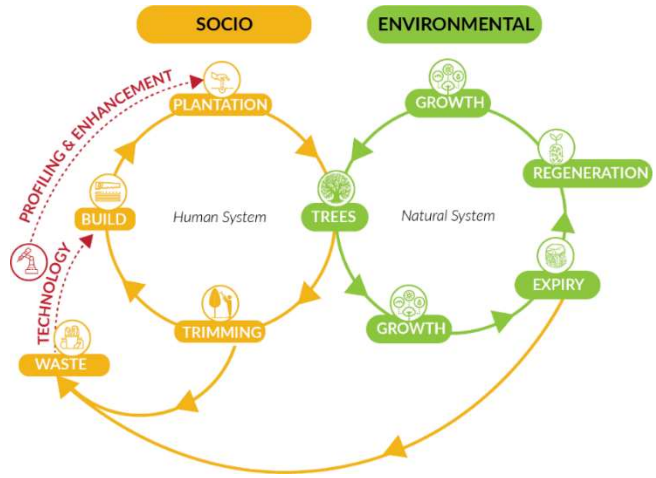

Figure 2 Diagram showing the proposed socio-environmental system

2. Potential Synergies of Urban Tree Systems

In the United States, tree planting has been a significant activity associated with urban built environment growth due to the beliefs of tangible and intangible urban tree benefits (Dümpelmann, 2020 pp 402-404). Urban trees are mainly planted by two groups of efforts, the property owners planting trees in neighborhoods and city governments in charge of tree planting along large avenues or parkways (Lawrence, 2008). The ecosystem services provided by urban trees are broadly recognized and numerous municipalities have recently increased their efforts and resources in urban tree planting (Conway, 2016, pp 23-24). Many local governments in the United States have launched tree planting programs, e.g., the Million Tree Program in Los Angeles, for their multiple environmental and health benefits (Pincetl et al., 2013, p 475). The success of tree planting efforts depends on careful planning and requires a multifaceted decision-making process (Brancalin et al., 2020, p 2349, Holl and Brancalin, 2020, p 580). Trees are also voluntarily planted by residents in their own properties. Urban residents collectively manage a significant portion of the urban forest as the majority of urban trees are located on private properties. Research efforts have been conducted on tree canopy composition in US residential areas (Avolio et. al., 2018; Bonney and He; 2019, Koeser et al, 2014; Lin et. al., 2021; Pincetl et. al., 2013).

However, there exists many gaps in the current studies of urban trees benefits. First, the benefit of urban trees as building materials has rarely been recognized and acknowledged in literature. In a systematic literature review of urban tree benefits, 37 benefits were summarized. None of these papers reviewed mentioned the benefit of urban trees as building materials (Roy et al., 2012). Recent scholarly works started to call for using urban trees for lumber and construction materials (Nowak et al., 2019, p 4, Grohmann et al., 2019, p 178), but it remains limited and often focused on firewood (Turner-Skoff & Cavender, 2019, p 327). Second, these studies do not generally focus on urban tree growth as a dynamic model. Trees grow and change with time, which causes costs and affects other infrastructural systems. Urban trees require maintenance and cities, neighborhoods and/or individuals are constantly trimming their trees in order to maintain their properties and public rights of way for human access and for access of their public utilities. Where this waste material goes depends on specific municipalities and individuals' sustainable foci, but even in fairly progressive cities like Tucson, Arizona, much of the material still ends up in landfills, weakening the net benefit. Lastly, there are no additional socio-environmental connections, such as the use of this waste as construction materials, especially to aid in addressing society's need for affordable housing.

Historically, urban development is primarily constrained by geographical location and its carrying capacity, which primarily is determined by the availability of resources and shelter (Wang et. al., 2020). Trees are important to societies (Elmendorf, 2008, pp 152-156) and there is a long history with native trees for a variety of purposes like foods, medicines, firewood, charcoal, animal feed, pollen for nectar, tools, textiles, timber, posts, shelter and worship. Unfortunately, non-native vegetation currently dominates the nursery industry, displacing the usefulness and knowledge of native tree resources. As the world became increasingly urbanized and globalized, this need for local sourcing was no longer seemingly required, as we improved the ability to transport material and ideas. Culturally and physically our built environment became more homogeneous as there was less place-based design and use of local materials, which in part has led to less environmentally tuned buildings and cities. The construction industry is one of the largest consumers of natural resources in the world (Adriaanse et al.,1997), so it urgent that this industry should be part of the solution moving forwards. Studies suggest simple substitutions to timber would save 14-31% of global CO_2 emissions, without factoring in the potential of timber as a broader process and practice beyond isolated buildings. (Oliver et al, 2014, p 248)

Today, timber is the only renewable material used by architects and the construction industry. Other biotic materials have future sustainable potentials, vs slower forming geologically based materials e.g. mycelium and plant fibers, but are not currently industry norms. The underutilized potential of wood in face of our modern challenges is captured here:

> "While it is one of the world's oldest and most utilized materials for construction, wood was soon eclipsed in modernity by steel and concrete. Today, wood's ability to sequester carbon, its relatively rapid cycles of regrowth, it's material flexibility for reuse and adaptation, and its unique aesthetic and performative qualities have triggered widespread interest in reviving and intensifying its use. And yet, while wood has been posited as a construction material for the twenty-first century it remains largely unknown and abstract." (Ibanez et al., 2019, p 10).

Beyond the actual proposed material-scale research of properties and prototyping of new environmentally tuned, parametric material assemblies, the unique spatial and temporal implications of using wood at multiple scales also needs further research and synthesis; we propose connecting architecture and construction with larger forestry ecosystems and carbon cycle dynamics in new network typologies.

3. Building Inter-connected Scales of Urban Tree Inventory

Previous studies identified three scales of 'human drivers' related to urban tree planting and conditions: "the municipal-regional scale, capturing government ordinances and market and economic influences; the neighborhood-scale, reflecting formal and informal institutions related to social norms and structure; and the household-scale, representing attitudes, knowledge and household structure" (Conway, 2016, p 24). A system-based design modeling is needed to synthesize solutions from complex scenarios and multiple strands of data. The complex and dynamic scenarios link human and ecological systems in the urban environment to foster optimization and expansion of both. As climate change pressures continue to challenge our "business as usual" model, it is also important to include in our understanding the socio-environmental opportunities for energy use and construction materials and processes in city greening. "There is a common conceptual framework underlying all these complex phenomena and that the dynamics, growth and organization of animals, plants, human social behavior, cities and companies are, in fact, subject to similar generic 'laws." (West, 2017, p 5) At its core, the methodological framework insists upon inter-scalar observation and data collection, modeling, tracking and performative analysis as green waste and material supply chains have micro to regional implications and connections. This digital modeling process will be a research project in itself as material and building scale software and regional data and mapping technologies are still developing their interfaces to each other.

As an illustrative example, we explore Mesquite trees (*Prosopis sp.*), which are a native, relatively fast growing, abundant local tree species with low water requirements, in the City of Tucson, Arizona (See Figure 3) and across the Southwest United States, as well as in most of the arid regions of the world. The relationship to construction is intended to increase sustainability on multiple levels. This example tree and geographical location provides a model which can be translated and adapted to other tree species and geographical locations in a variety of climates and areas across the globe.

Figure 3 Tucson, Arizona located in the arid region of the Southwest United States near the border with Mexico (highlighted with a star).

Mesquite trees in the Sonoran Desert region have a 12,000-year history of supporting human life (Bell and Castetter, 1937, pp 3-47). However, globalization and colonial industrialization have disrupted the use of mesquites as a construction staple. Today in the Southwest Region, they are commonly used in the urban environment for shade cover and aesthetics. Mesquite trees in Tucson, are an abundant regional natural resource that are grossly underutilized. With optimal urban modeling we could align with city goals of tree plantings for shading and beautification, water reduction, green infrastructure with management for utilities, safety and accessibility toward an integrated living urban forest system, rather than a forest grown separate from the city, exclusively for construction materials, which is typically the norm today (See Figure 4).

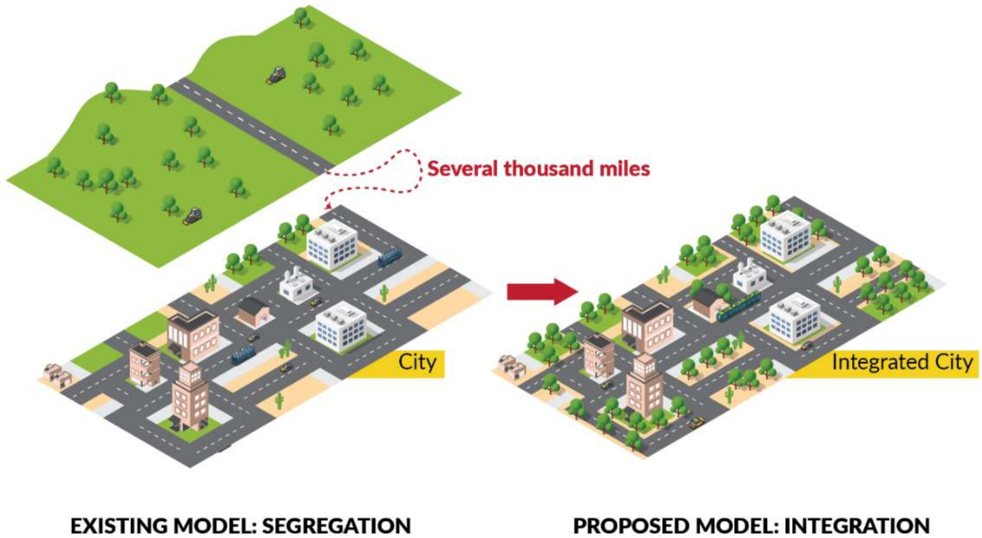

Figure 4 Diagram of existing separate system vs. proposed integration of urban forest

Past infrastructure investments created path dependencies that can limit the space available for urban nature, reduce demand for the services provided by green infrastructure or decrease its effectiveness relative to grey alternatives (Keeler et al., 2019, 29-38). Cities, like Tucson, located in a desert environment with high heat and solar intensity and extensive pavement while lacking large areas of green infrastructure, may see the greatest benefits from urban trees.

Current practices of urban forestry mapping involve multiple methods. Remote sensing is a broadly used method, especially the Light Detection and Ranging (LiDAR) and hyperspectral remote sensing (Shahtahmasseb et al., 2021, p 4). High-resolution images can be used to identify and map the mesquite trees around Tucson to understand how the extent of their spatial cover, health, and biomass tend to change over time and respond to prevalent environmental and climatic drivers (temperature, but mostly precipitation in this region). The high-resolution images used in the classification are usually from a single time period due to the high acquisition cost. To assess change in these trees, medium resolution images are usually preferred since they provide multi-temporal time series that should capture change over time. In addition, public participation and field surveys assisted with Geographic Information System (GIS) online technologies can aid in collecting existing mesquite tree distribution information. A variety of citizen science platforms have been developed for crowdsourced urban forestry mapping, e.g., OpenTreeMap, Treezilla, and Smart Trees Pacific. Online platforms can be developed to collect, share, and visualize mesquite tree distribution and needs in Tucson, Arizona, giving agency and motivation to more community members. The results of combining various scales of remote sensing technologies and citizen science methods can help validate each other and enrich the spatial distribution information of mesquite trees as well as aid in determining the appropriate allocations for construction materials versus mulch or other prospective uses for the green waste (See Figure 5).

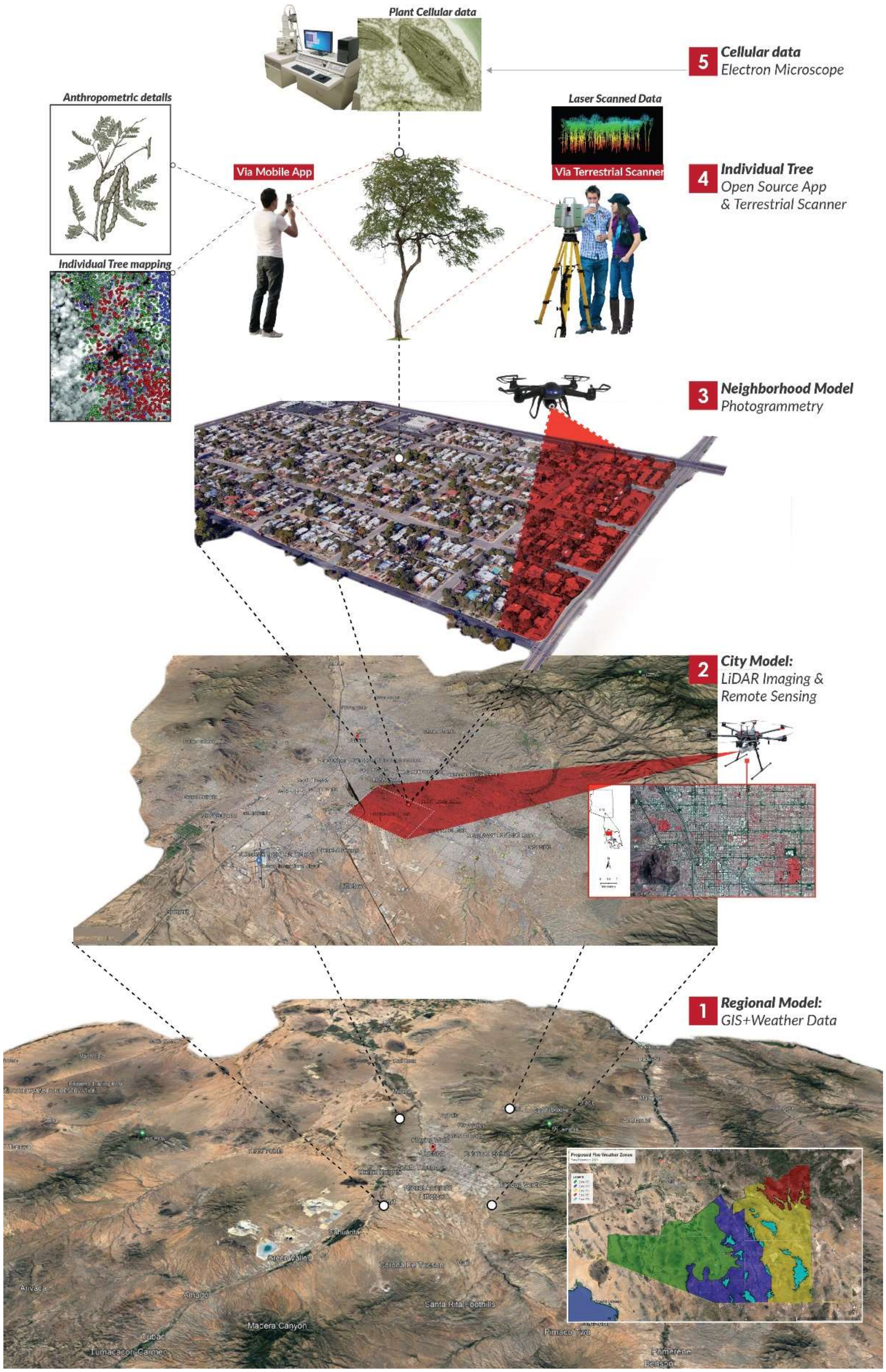

Figure 5 Diagram showing inter-connected scales of data collection

4. From Mass Production to Mass Customization

The dynamic, digital models will be an inter-scalar resource, connecting regional geographical and climate data with those of specific neighborhoods and tree types. Additionally, these models will also be linked to parametric Building Information Models, which will hypothesize on and prototype various construction projects with this new local, quantifiable, sustainable resource. Examples of construction projects and physical prototypes will be developed along two parallel trajectories, relating to the scale and process of the timber trimmed (See Figure 6).

Digital fabrication is considered to be the most disruptive advancement in the construction industry since the industrial revolution. Now advanced systems of additive and subtractive fabrication are becoming smaller, cheaper, faster and therefore more accessible to more groups. The ability to produce in large quantities irregular building components with the same ease as standardized parts has introduced the notion of mass customization into building design, fabrication and construction. In many cases it is just as easy and cost-effective for a Computer Numerical Control (CNC) milling machine to produce 1000 unique objects as to produce 1000 identical ones. This means that for the first time in history we can now make the shift from mass production to mass customization. This ability to customize means that we can now achieve site and environmentally specific optimized forms in architecture, which are built affordably with factory production quality specifications (Dunn, 2012; Meredith, 2008; Parmar & Dickinson, 2018, pp 406-414).

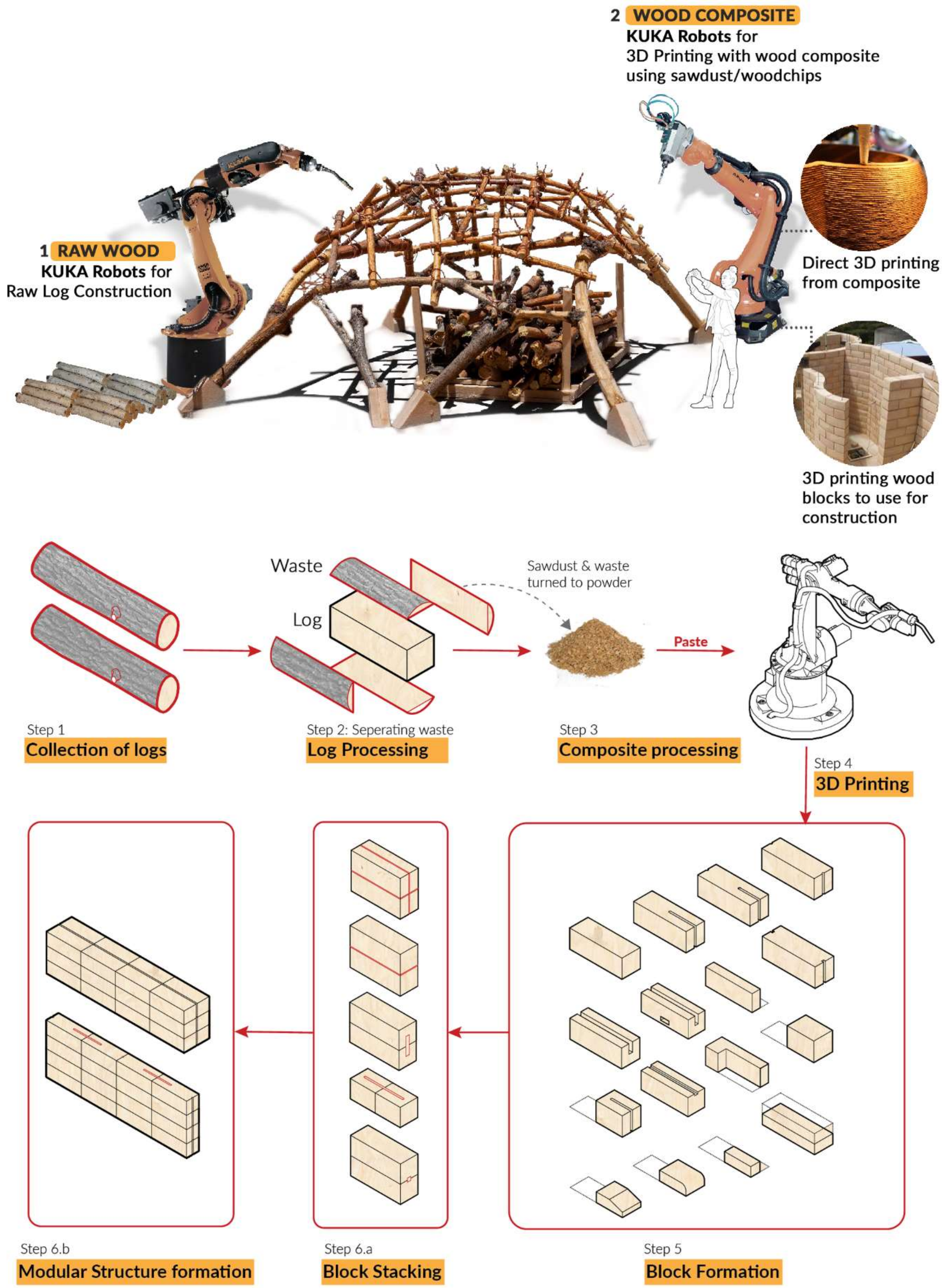

Figure 6 Diagram showing two parallel prototyping tracts; raw wood and timber composite

This ability to now make affordable, bespoke forms of architecture and construction that are more energy efficient and climatically adaptable, means that trees that are less-uniform in their form (i.e., not literally tall and straight), like the mesquite or smaller diameter lumber, which is often the by-product of thinning for wildfire prevention, can be utilized in ways that industrialization previously ignored. (Kolarevic & Parlac 2015; Monier, 2013, pp 2337-2343; Whole Trees, 2022) The cost and increasing portability of CNC tools also means these can be utilized on the ground by community groups rather than having to have large-scale machinery and corporations involved. (Risen, 2018; Taubman College of Architecture and Urban Planning, n.d.). An additional precedent is the graduate work of the Design and Make program of London's Architectural Association, which exists on a rural, woodland campus on the south coast of England. Here students are developing experimental forms with non-uniform wood typologies with advanced forms of fabrication. Another great example is the work of Achim Menges and his students at the Institute of Computational Design in Stuttgart, Germany. Their focus is primarily on wood and biomaterials with recent work looking at lightweight applicability and 4D printing, i.e. adaptive 3d printing technologies.

Apart from using the waste raw material in new ways, we also propose a novel 3D concrete printing material system that incorporates wood fibers locally sourced from these waste products. In the case of mesquite trees, fibers have been shown to function well for reinforcement, enhancing the tensile and flexural strength (Velagala et al., 2017, p 1387). Additionally, wood fiber is lightweight and offers better hygrothermal properties (Kuqo and Mai, 2021, pp 2). The addition of wood fibers can also mitigate the adverse effects of crack initiation and propagation through bridging action (Tonoli, 2010, 230-231). In the case of other tree types specific material research would need to be done to achieve optimal performance criteria as each species varies. There would also be potential differences related to parts of the tree, older growth vs. newer growth etc., these details would obviously be important parts of a successful implementation of this concept, as sorting into species and sizes with some knowledge would be crucial. In this particular case the discussed species is fairly dominant and distinctive, so that part of the sorting process would not be too cumbersome.

With climate change, cities in the Sonoran Desert are facing increasing challenges of water shortage, more frequent extreme heat and worse flooding (Brazel, 2019). While urban trees can provide multiple functions to the society in mitigating those challenges, most of the benefits are intangible and difficult to measure. An online platform can be developed to survey the public's decision-making process on urban tree selection with the focus on mesquite trees. The targeted survey participants should include the two major groups in urban tree planting (i.e., city governments and local residents) and also commercial property developers, HOAs, other types of land owners. These strategies connecting private citizens to public institutions, including the academy (faculty and students) will enable a more rounded approach and allow multiple forms and types of feedback to be integrated into the research process, which will be vital in pushing the work forward into real-world actionable items for our society at large (See Figure 7). The online platform would also be a tool for education and dissemination on the relationship of green waste to construction materials, which with feedback will help determine more appropriate planting strategies moving forwards. The platform would ideally be able to adapt to incorporate future data, i.e. be a live tool, which would attempt to quantify more benefits and relationships of urban trees as they become known to continually improve the synergy between our natural and human-based systems and infrastructure. Understanding the complexity of our actions is key to a more sustainable future.

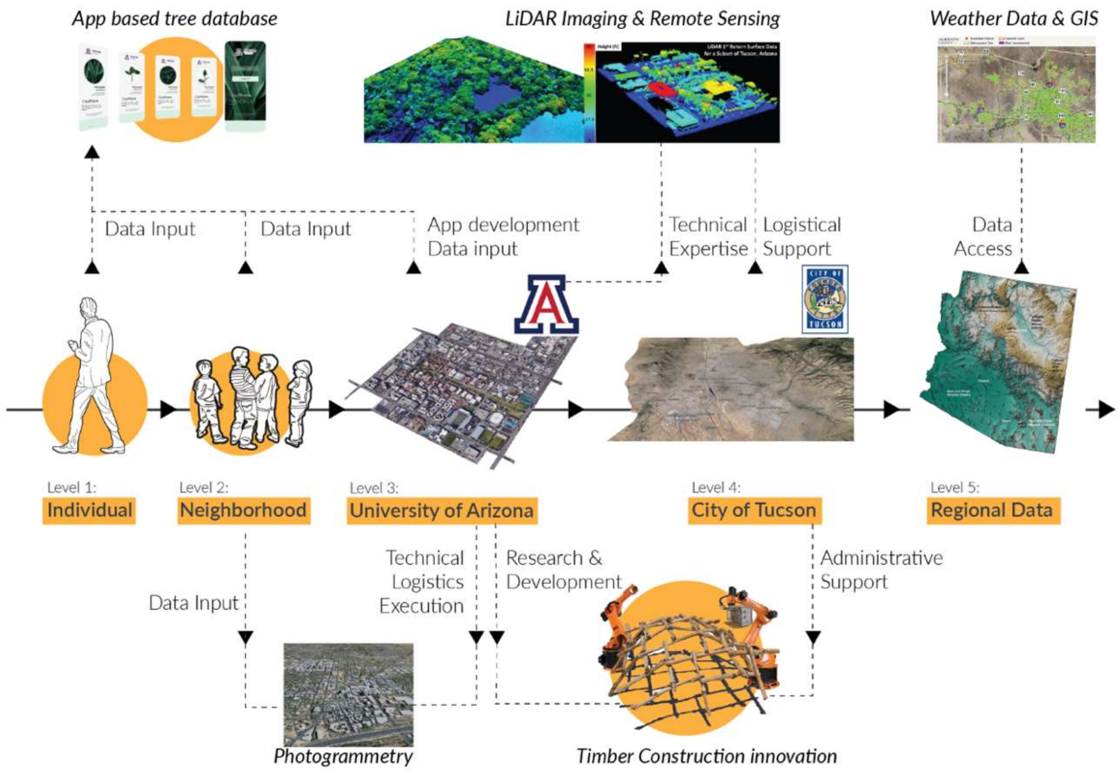

Figure 7 Diagram showing potential range of participants

5. Conclusion: Global relevance with local applications

Architecture and the building industry is an oft ignored part of our energy and climate crisis to those outside the related professions. The built environment ties into multiple sources of emissions including land use, transportation, industry and power, giving multiple parameters and complexity to the measurements and studies of building life-cycle assessments and embodied energy. Architecture 2030 states that the built environment is responsible for 40% of annual global CO_2 emissions via data from the International Energy Agency. Regardless of the exact specifics looking at ways to move sustainably forward in this area are key to human survival and slowing the climate crisis. Part of the solution is using more locally based sustainable materials. We discussed using the example of a specific native tree and city, but this model is transportable to other tree species in other cities around the globe, beyond the southwestern United States and arid climates. Each species will have differing properties in itself and to the environment around it, these parameters ideally would be factored into the iterative design and making process to achieve greater diversity of forms and applications in our built environment endemic to local identities. This research model could also be adapted for other local materials e.g., earth and clays helping provide a more circular economy and methods to track the inter-relationships of materials to construction with regional form in our built environment.

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