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Life Cycle Assessment of Ecosystem Services for Phoenix's Building Stock

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Abstract

Better methods are necessary to fully account for anthropogenic impacts on ecosystems and the essential services provided by ecosystems that sustain human life. Current methods for assessing sustainability, such as life cycle assessment (LCA), typically focus on easily quantifiable indicators such as air emissions with no accounting for the essential ecosystem benefits that support human or industrial processes. For this reason, more comprehensive, transparent, and robust methods are necessary for holistic understanding of urban technosphere and ecosphere systems, including their interfaces. Incorporating ecosystem service indicators into LCA is an important step in spanning this knowledge gap. For urban systems, many built environment processes have been investigated but need to be expanded with life cycle assessment for understanding ecosphere impacts. To pilot these new methods, a material inventory of the building infrastructure of Phoenix, Arizona can be coupled with LCA to gain perspective on the impacts assessment for built structures in Phoenix. This inventory will identify the origins of materials stocks, and the solid and air emissions waste associated with their raw material extraction, processing, and construction and identify key areas of future research necessary to fully account for ecosystem services in urban sustainability assessments. Based on this preliminary study, the ecosystem service impacts of metropolitan Phoenix stretch far beyond the county boundaries. A life cycle accounting of the Phoenix's embedded building materials will inform policy and decision makers, assist with community education, and inform the urban sustainability community of consequences.

Background

Engineers are at a crossroads; for the first time they are being forced to consider the inherent natural resource, environmental, and social constraints that accompany human enterprise. Furthermore, how urban areas such as Phoenix, Arizona import goods to support urban living, for example building materials, can have far reaching impacts outside of the city, including through supply chain networks. Strategies to improve urban sustainability must consider supply chains, or the ability of global networks and surrounding regions to supply natural resources and process waste outputs (Chester, Pincetl, & Bunje, 2012). It can be argued that a city that takes in more resources than its outlying region can provide, or generates more waste than its outlying region can assimilate, is unsustainable (Goodland & Daly, 1996).

Beyond resource availability, an additional set of constraints needs to be considered in engineering decision making. Ecosystem services are the human benefits derived from ecosystems which the Millennium Ecosystem Assessment (MA) defines as "dynamic complex[es] of plant, animal, and microorganism communities and the nonliving environment interacting as a functional unit" (Arico et al., 2005). Ecosystem services range from climate regulation to food provision to disaster security. These form the foundation for what the MA describes as "human wellness" (Figure 1).

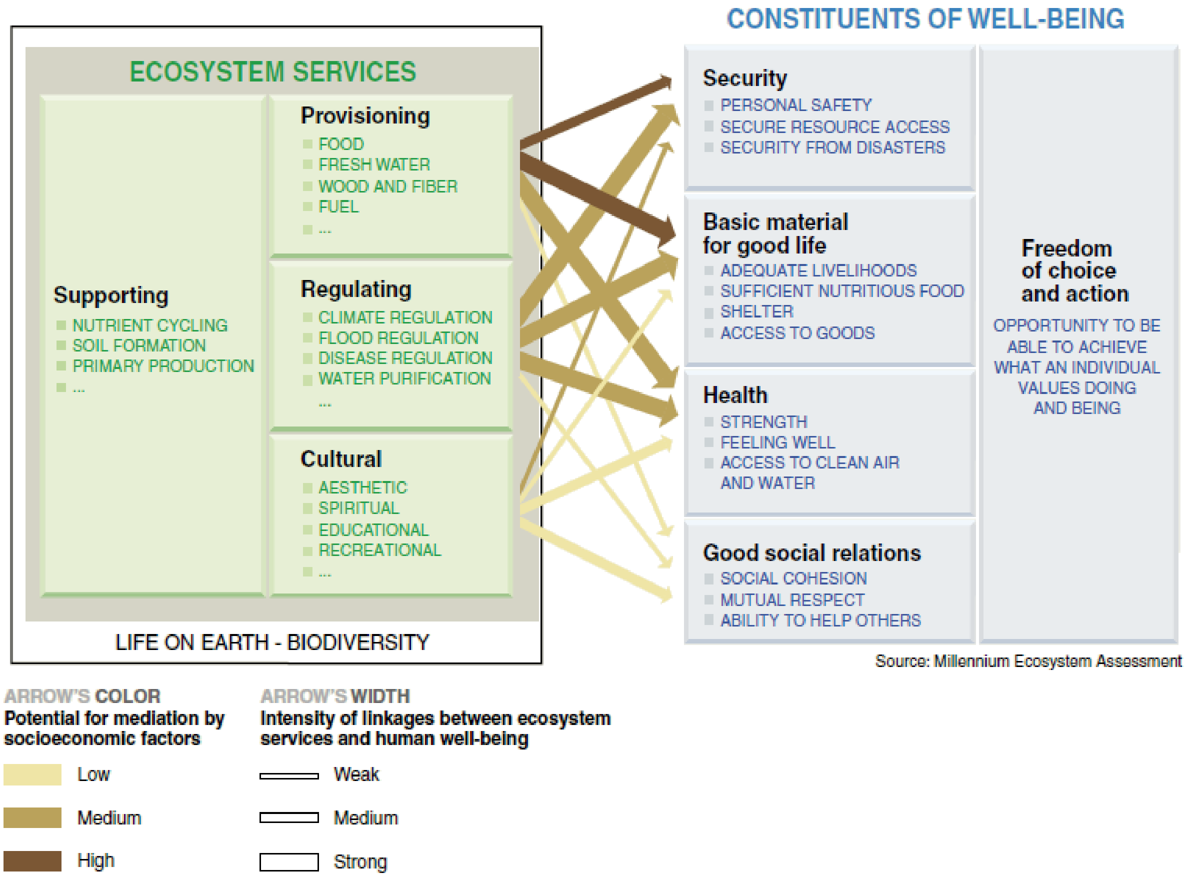


Figure 1: Linkages between Ecosystem Services and Well-Being (MA 2005).

Because these services are often indirectly gained from the natural environment there is a poor understanding of the linkages between human activity and decreases in ecosystem services. Current frameworks for assessing urban sustainability do not connect physical flow metrics (energy use, water use, air emissions, solid waste generation, etc.) to human and environmental or ecosystem service impacts. It is well documented that current city structures are unsustainable and produce inequitable burdens through environmental, economic, and health impacts to both those living directly in urban environments as well as those outside who are indirectly affected (Kennedy 2010, Kennedy 2007). In order to fully understand the potential for improvements, a more rigorous framework is needed to assess these ecosystem service impacts and to incorporate the links between technological and natural systems (Table 1).

Table 1: Millennium Assessment Ecosystem Services

Provisioning		**Cultural**
Food	Crops	Cultural Diversity
	Livestock	Spiritual and Religious Values
	Marine Fisheries	Knowledge Systems
	Aquaculture	Educational Values
	Wild plant / animal products	Inspiration
Fiber	Timber	Aesthetic Values
	Cotton, hemp, silk	Social Relations
	Wood fuel	Sense of place
Fresh Water		Cultural heritage values
Biochemicals, natural medicines, pharmaceuticals		Recreation and Ecotourism
Ornamental Resources		
Genetic Resources		

Supporting Services	**Regulating Services**
Soil Formation	Air quality Regulation
Photosynthesis	Climate Regulation
Primary production	Water Regulation
Nutrient cycling	Erosion Regulation
Water cycling	Water Purification / Waste Treatment
	Disease Regulation
	Pest Regulation
	Natural hazard regulation
	Pollination

LCA emerged in the 1970s to assist chemical engineers in understanding toxicity impacts (Hendrickson 2006) but has grown and been formalized for the flexibility of evaluating any product, process, service, or activity. The formal LCA steps are goal and scope definition, inventory analysis, impact assessment, and interpretation. The goal of an LCA is to assess all relevant human and environment impact categories, including those which are ancillary. This is extremely important, as the majority of impacts could potentially exist in the outlying city regions as opposed to processes directly within a city (Chester and Horvath 2009).

Incorporating ecosystem services into infrastructure LCA presents a unique but important challenge for the LCA community. Without an accounting of the changes in ecosystem services, LCAs focused on urban areas could yield unsustainable conclusions. For example, if only greenhouse gases (GHGs) are considered, the GHG emissions might be reduced at the expense of drastically deteriorating pollination services. Developing a comprehensive suite of impact categories in LCA will improve the ability to make sustainable decisions in urban environments.

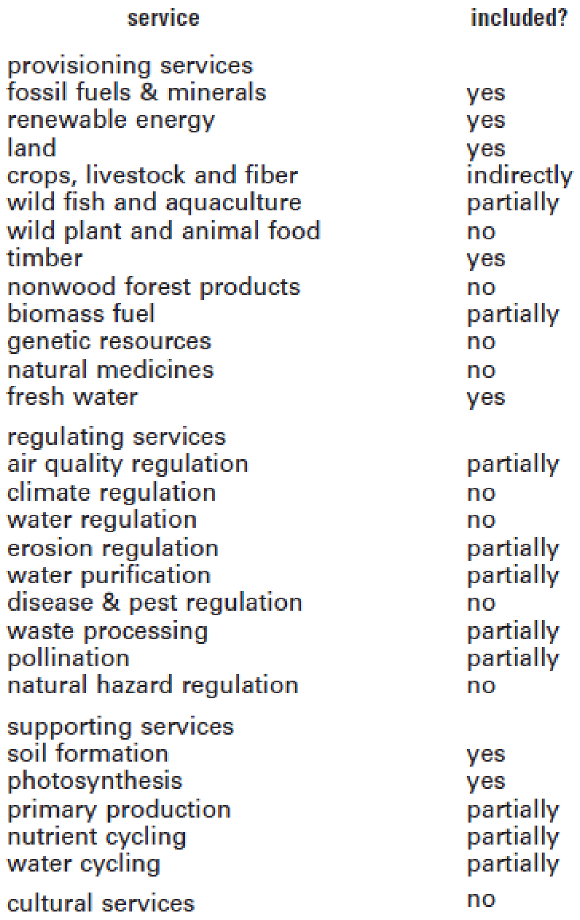
Goal

The goal of this research is to develop a methodology for assessing the ecosystem services impact from the use of building construction materials in the Phoenix metropolitan area through the use of LCA. This methodology identifies the weaknesses of current LCA approaches in analyzing ecosystem services. An LCA including the connection between human materials and ecosystem services would prove invaluable in policy development by allowing a clear comparison of the consequences of damage to ecosystems alongside other LCA categories such as climate change and impact to human health. The research will provide a rigorous assessment of material inputs to construction, accumulation effects, waste outputs, and the corresponding ecosystem impacts.

The methodology will aid urban sustainability assessment, using buildings in the Phoenix area as a case study. The ecosystem service impacts considered are ecotoxicity, acidification, eutrophication, and land transformation.

Previous Work

The Millennium Ecosystem Assessment, ordered by the UN and completed in 2005, classified the ecosystem services which benefited humans and commented on their relative improvement or degradation given rapid human and technological development (MA 2005). Ecosystem services were aggregated into four major categories: provisioning services, regulating services, cultural services, and supporting services. Traditional life cycle impact assessment methods call for provisioning services such as food, fuel, and material resources to be considered. A comprehensive inventory of present inclusion of these ecosystem services in LCA was performed by Zhang, Singh, & Bakshi, 2010. In a second paper, Zhang, Baral, & Bakshi, 2010 introduced a web tool called Ecologically Based LCA (Eco-LCA) that includes new impact categories to account for more ecosystem services (Figure 2).



service	included?
provisioning services	
fossil fuels & minerals	yes
renewable energy	yes
land	yes
crops, livestock and fiber	indirectly
wild fish and aquaculture	partially
wild plant and animal food	no
timber	yes
nonwood forest products	no
biomass fuel	partially
genetic resources	no
natural medicines	no
fresh water	yes
regulating services	
air quality regulation	partially
climate regulation	no
water regulation	no
erosion regulation	partially
water purification	partially
disease & pest regulation	no
waste processing	partially
pollination	partially
natural hazard regulation	no
supporting services	
soil formation	yes
photosynthesis	yes
primary production	partially
nutrient cycling	partially
water cycling	partially
cultural services	no

Figure 2: Ecosystem Service Inclusion in Eco-LCA (Zhang, Baral, et al., 2010)

The Eco-LCA tool has included many new ecosystem service impact categories, such as pollination, but has stopped short of providing a process-based approach of including ecosystem services in LCA. Instead, the impact categories have been linked to Economic Input-Output LCA, which models the entire 1997 US economy as 491 sectors (Hendrickson, Horvath, Joshi, & Lave, 1998). The advantage of this approach is that no section of the system boundary is "cut off", which is consistent with systems-oriented thinking. The disadvantages of this method are the loss of detail in specific processes since impacts are aggregated by sector and the loss of regional specificity by presenting US average impacts (Zhang, Baral, et al., 2010). Studies have shown that spatial scale is especially important in developing new ecosystem service impact categories (Saad, Margni, Koellner, Wittstock, & Deschênes, 2011). A process-based LCA would be a more appropriate approach since it considers the exact processes and accompanying impacts. The following methodology provides a framework for such a process-based approach.

Methodology

This project incorporates ecosystem service impacts within the current LCA framework to highlight the potential of further integrating ecosystem services in LCA. This is done through a case study of buildings in Maricopa County, Arizona. Current day buildings are inventoried by the Maricopa County Assessor's Office. The assessor data, which provides information such as size, year of construction, and building type (single family detached home, office building, warehouse, mall, etc.), is coupled with building material estimates from RSMeans (RSMeans 2008). Building material models were developed for 6 residential classifications, 8 commercial, and 1 industrial (Table 2). The Athena Impact Estimator software was then used to assess each model. Aggregating the buildings into multiple categories allowed for a more detailed analysis since construction materials and quantities vary based on building type.

Table 2: Building Classifications

Building Category	Classification
Industrial	Industrial
Warehouse	Commercial
Highway Retail	Commercial
Mall/Big Box Retail	Commercial
Neighborhood Retail	Commercial
Office Space	Commercial
Hospitals	Commercial
Education Buildings	Commercial
Government Buildings	Commercial
Single Family Detached Homes	Residential
Joined Luxury Homes	Residential
Joined Economy Homes	Residential
Low-rise Luxury Residential	Residential
Low-rise Economy Residential	Residential
Mobile Homes	Residential

By building count, 90% of the buildings in Maricopa are classified as residential, with commercial and industrial buildings comprising 9% and 1% respectively (Maricopa County Assessor, 2012). Different building categories have different material requirements and material quantities, so dominating building count does not necessarily translate to dominating impacts.

Athena is an LCA software which calculates impacts according to the US EPA's TRACI indicator system (Bare 2002). In order to use additional impact assessment methods beyond TRACI, Athena was used only to gain material totals for each building classification in this study.

Lack of region-specific databases and impact assessment methods are major challenges in LCA (Owens, 1997). Many impact assessment methods were developed in Europe, and the resulting characterization factors are sometimes used as proxies for impacts in the US or elsewhere. When European technologies and manufacturing processes are similar to those being assessed in the US then European impact factors can be used as proxies provided uncertainty is assessed. The EcoInvent Database version 2.2 was used to obtain information on the indicators for this study (Table 3).

Table 3: EcoInvent Impact Categories

Impact Methodology	Used Categories	Ecosystem Service Category
Cumulative Energy Demand	All	Provisioning
Cumulative Exergy Demand	All, minus minerals	Provisioning
Ecosystem Damage Potential	All	Regulating / Supporting
Ecological Footprint	Total Land Use	Regulating / Supporting
Tools for the Redution and Assessment of Chemical and Other Environmental Impacts (TRACI)	Eutrophication, Ecotoxicity, Acidification	Regulating / Supporting
Environmental Design of Industrial Products (EDIP)	Eutrophication, Ecotoxicity, Acidification, Photochemical Ozone Formation (vegetation)	Regulating / Supporting

This study is a cradle to gate assessment and includes extraction of primary materials through building material production at the factory gate. The transportation from the factory to the construction site and the equipment use in building construction are excluded in this assessment. This means that results are likely conservative.

EcoInvent material processes were joined with the building material models to determine impacts. The impacts are then normalized based on the square footage of the category model buildings. The normalized factors were joined with the Maricopa County assessor data to determine regional impacts.

Results

Several provisioning, regulating, and supporting services are assessed. Cultural services are not included because they are anthropocentric value based services (Zhang, Singh, et al., 2010). Potentially in the future they could be included using valuation methods such as contingent valuation (Tietenberg and Lewis, 2010). The results are intended to provide foundational measurements of critical impacts, and demonstrate the potential of incorporating LCA as a tool to assess more complex and detailed ecosystem services.

Provisioning Services

The two main impacts assessed for provisioning services are Cumulative Energy Demand (CED) and Cumulative Exergy Demand (CExD). At the most basic level, these impact categories seek to quantify the total amount of energy necessary to provide goods and services. Energy is a basic, familiar indicator. Exergy, in contrast, provides information on the quality of the available energy. Energy as a resource can never be destroyed, according to the first law of thermodynamics, but is merely transformed to a different form. What is lost in the use/transition of energy is the availability; according to the second law all processes in total move to disorder (less availability). Exergy accounts for the available work from a resource. For example, when coal is burned the energy stored in the bonds in transferred to heat which eventually dissipates into the environment. Although the energy is not destroyed, the usefulness of that energy has been lost. Further information on the CExD indicator can be found in the report Bosch et al. 2007.

For non-renewable resources CED and CExD yield nearly identical results, since CExD is the total exergy of resources removed (Bosch 2007). However, if a different exergy method, such CEENE, were applied instead, results could vary greater. One of the advantages of the CEENE indicator is the inclusion of exergy extracted from the natural environment due to land change; this is not considered in the CExD indicator (Dewulf et al., 2007).

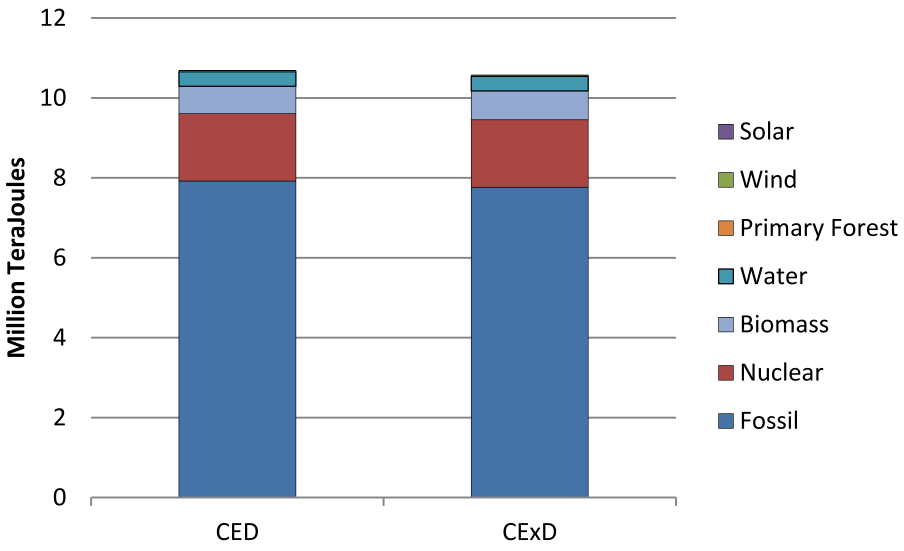


Figure 3: CED vs. CExD of Maricopa County Construction Materials, 2012 Building Stock

Energy and exergy yield nearly identical results for construction materials, due to the heavy reliance on fossil fuels. Virtually all of the energy contained in fossil fuels can be converted to usable energy. The same could not be said for solar energy. As noted previously, the residential sector accounts for over 90% of the building stock by count of buildings. When compared by total CED and CExD for the sector, residential is still the dominant energy consuming sector (Figure 4). Material use for residential buildings is a key driver of energy use in the building stock. This is important for policies aimed at regulating building materials.

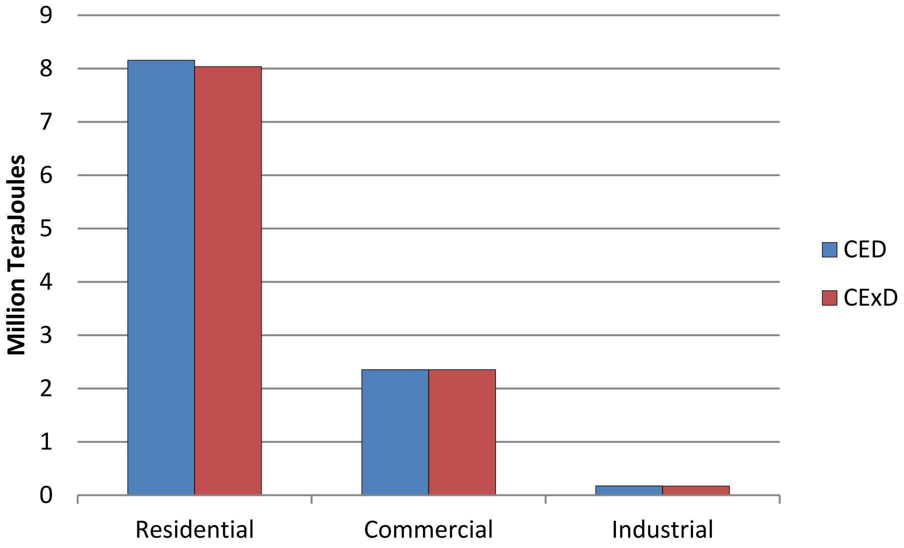


Figure 4: Phoenix Sector Comparison, 2012 Building Stock

Regulating and Supporting Services

Regulating services such as natural water purification, climate regulation, natural pest regulation, and natural disaster buffering are difficult to directly measure and quantify. Even more difficult to quantify are indirect supporting services such as photosynthesis, soil formation, and nutrient cycling due the complexity and prevalence of the processes. Choosing a measurement technique or unit of measurement for a category such as "pest regulation" implies an anthropocentric viewpoint since humans will define pests differently than other organisms in the ecosystem. This could potentially limit a systems-level understanding of the impacts. For this study, instead of directly trying to measure changes in ecosystem services, impacts were chosen that change the functionality of these services.

In LCA, there are two major ways for reporting the final results. For methods such as TRACI the final results are reported as impact potentials, quantified on a unit of common comparison. This is known as a midpoint methodology, as it stops short of predicting the actual impacts of processes. In contrast, endpoint indicators directly quantify damage (impacted populations, land area, etc.) This can be useful in fully understanding the consequences of products, but the results should be used with caution since the assumptions of arriving at these consequences are embedded in the model, and have not been adapted for all local conditions. A summary table comparing the US TRACI indicators with the endpoint quantities from the Danish EDIP method is given below (Table 4).

Table 4: TRACI and EDIP Comparison

	TRACI		EDIP	
Acidification	1.64E+11	moles H^+_{eq}	5.14E+10	m^2
Photochemical Ozone (Vegetation)	-		3.59E+12	m^2.ppm.h
Eutrophication	1.17E+08	kg N	2.69E+09	kg NO_3^-
Ecotoxicity	3.28E+11	kg 2,4-D_{eq}	4.03E+14	m^3 water (chronic)
Ecotoxicity	-		6.96E+13	m^3 water (acute)
Ecotoxicity	-		3.41E+12	m^3 soil

It is important to note that the EDIP indicators represent damages to certain areas, such as m^3 of damaged soil. While this will probably impact the functioning of ecosystems, it is not a direct quantification of the damages to the ecosystem service outputs.

Ecosystem Damage Potential (EDP) is an indicator that captures the loss in species diversity due to land change and occupation. In the indicator, changes are normalized to a points scale to allow for comparison between different products or processes. Included in this indicator is the amount of time for land to transition back to the original purpose and species diversity (Frischknecht et al., 2007). For Maricopa County building stock, the EDP totals to 1.79×10^{11} points.

EDP is useful for providing a quantification of ecosystem damage due to land change; however, a comparison point is needed to interpret the meaning of this indicator. This is because EDP gives results as points which are not easily interpreted outside the context of LCA. EDP is best suited for similar product comparison, because the points indicator is meaningless without a reference point. EDP was developed for central Europe, and thus could provide inaccurate results for other geographic regions. An improved understanding in differences in land types, species diversity, and international supply chains could provide a more accurate application of this indicator to Phoenix. EDP represents changes both inside and outside Phoenix (i.e. land changed to produce lumber). Further work is needed to integrate EDP into ecosystem service LCA.

Ecological footprint is an easily interpreted indicator that reports the amount of land necessary to support an activity or process. For this study, the amount of land necessary to support the manufacture of materials for the construction of the building infrastructure of Maricopa County was calculated (Table 6). Comparing this to the actual land area of Maricopa County supports the idea that cities are resource islands, pulling nutrients from outside their geographic boundaries to support their activities *(*Perrone et al. 2010).

Table 5: Maricopa County Ecological Footprint Compared to Land/Population Ratios

	Size (mi^2)	Population
Phoenix Building Ecological Footprint (1 year)	**120,709**	**3,880,244**
Maricopa County	9,224	3,880,244
Arizona	113,998	6,482,505
United States	3,794,100	311,591,917
World	57,258,915	6,973,738,433

Comparing the total area of the state of Arizona to the ecological footprint of Phoenix building stock alone it is estimated that Maricopa County requires more land than the area of the state. The materials for the existing buildings of Phoenix have already been manufactured, in many cases over 30 or 40 years ago. Ecological footprint is reported as annual land area. In reality, the 120,000 mi^2 area to support this activity has been used over a period of time, not within a single year. Regardless, to produce materials for construction of the building environment of Phoenix is enormous, more than 13 times the physical size of Maricopa County. Future work should develop a material use curve which compares material production over time which can be used for more accurate indicators as ecological footprint assumes that all activities are happening in the present.

Discussion

Phoenix's impacts have occurred over time and space as the city has grown, not just in a single year or locale. This could mean decreased ecosystem functionality at less visible geographic locations, or slow, long-term decay of ecosystem services. Many of the impacts do occur very far away from Phoenix as supply chains often span countries or continents. This could be important for decision making focused on only on the Phoenix geographical area, because impacts outside the jurisdiction of a governing body might not be considered as important.

Further work needs to fully incorporate ecosystem service indicators into LCA. This study provides an example of how LCA can be used to assess large urban infrastructures. Improvements to this study would include adding a time-scale to building construction. All building models used in this study were assumed to be similar materials and construction methods to present-day construction. Although this is not a bad approximation since Phoenix is essentially a post-1960 city, differentiating between Phoenix-specific materials during different time periods could yield more useful results. Additionally, previously constructed and demolished buildings could be included in the study to gain insight into past impacts. Scaling the results to show a temporal trend of building construction and subsequent impacts (adjusted to previous technologies) could yield a more accurate trend of how Phoenix has impacted areas over time. Targeting key impact factors of past growth would help planners develop sustainable plans for future growth in Maricopa County. It is probable that a temporal study would reveal that the city of Phoenix has been reaching farther and farther geographically to obtain resources for construction; limiting or controlling this could lead to more sustainable growth.

To aide in decision-making, differentiating between local and remote impacts is a crucial next step in assessing Phoenix building stock. Different geographic regions and climates have different ecosystems, and thus unique ecosystem service resources. Identifying the location of manufacturing processes will help in creating a more accurate accounting of impacts and will highlight processes that impact unstable or critical ecosystems. When making decisions, policy makers should consider ecosystem service impacts in addition to traditional LCA indicators such as criteria air pollutants, GHGs, and resource depletion (water use). Local depletion of water resources could be an especially pertinent indicator for the Phoenix area due to the dry climate and scarcity of water.

Improving the quality of ecosystem service indicators is an essential next step in LCA. Ecosystems are very dependent on local climatic conditions so developing new, US-specific or regional-specific indicators will be extremely important. Developing new, innovative categories either quantitative or qualitative to describe the links between ecosystems and the technosphere is an important challenge to be addressed. This involves research both in improved LCA data aggregation as well as normalization methods as well as improved characterization of ecosystem service benefits> Work has been done in providing generalizable land classification factors, which have been tested in product-specific studies (Koellner et al., 2012; Milà i Canals, Rigarlsford, & Sim, 2012). These could provide a base for future ecosystem service LCA studies.

Buildings are a small piece of urban infrastructure impacts, but the Phoenix case study presented here shows the potential for ecosystem services to be incorporated into LCA. Once robust methods have been developed for accounting for ecosystem services in LCA, the assessment should be expanded to include other infrastructure systems such as transportation infrastructure, communications and electrical grids, and eventually economic networks. These complex systems characteristics could be matched with population growth patterns as well as quality of life indicators to identify potential pathways to a more sustainable future.

Conclusions

Current LCA methods do not fully capture the impacts to ecosystem services (Zhang, Singh, et al., 2010). This is due to the difficulty in quantifying ecosystem services, the variation between regions, and the lack of available data. The greatest remaining challenges to fully incorporating ecosystem services into LCA are 1) properly representing the role of ecosystem services in quantitative terms, 2) aggregating raw LCA data, and 3) properly accounting for direct and indirect human reliance on ecosystems (Zhang, Singh, et al., 2010). Future studies should focus on finding innovative ways to quantify and/or communicate the linkages between natural and anthropogenic systems.

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