Designing with a Carbon Conscience:
A web-based application to inform planning and urban design projects on potential carbon impacts.

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Abstract

This article is a summary of a broad research inquiry into embodied carbon and development of the Carbon Conscience design tool, an interactive design tool to assist designers with evaluating proposed urban design and planning projects in respect to carbon-related impacts. The inquiry included reviewing industry tools and resources as well as academic literature. This article details the subsequent methodology for developing the database used as the basis for the Carbon Conscience web application. The key metrics per land use (landscape, architectural, and ecological) considered are carbon emissions, storage, and sequestration. In addition to informing the database, the literature review revealed a number of key principles for designing with a Carbon Conscience as well as suggestions for further investments in research. The Carbon Conscience tool and database were developed with the support of a Sasaki Associates internal research grant.

Background

Across the design industry, from architecture to landscape, civil engineering to city planning, professionals are grappling with how to meaningfully address global climate change and the Anthropocene in our work. As designers we are optimists, and are looking for a way to build visions for a healthier, more equitable future. But as an industry, building and construction accounted for 39% of global emissions in 2019 (WGBC, 2020). Architecture 2030 estimates that the built environment and infrastructure combined contribute over 50% of current global climate emissions (Architecture 2030, 2020).

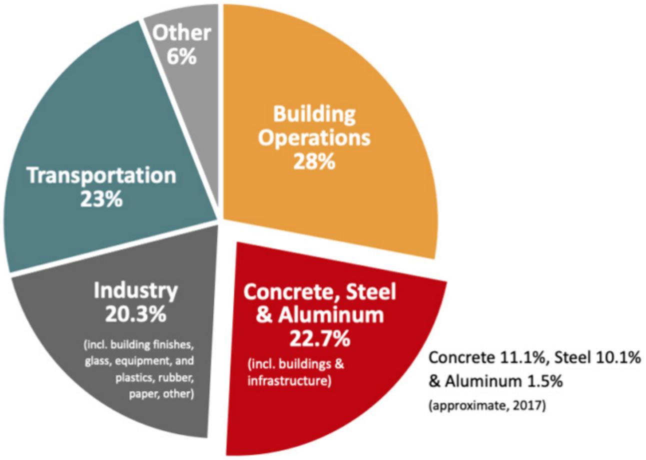


Figure 1:

Global CO2 Emissions by Sector (Architecture 2030, 2020).

The design industry has been addressing these issues through a host of high performance, low energy, and sustainable management strategies. For the last two decades, these efforts have broadly followed the Hanover Principles (McDonough and Braungart, 1992) laid out in 1992, developed and codified through the USGBC, BREEAM, Living Building Challenge, other NGOs, and building codes. Compared to earlier conventional approaches, these efforts represent a more environmentally responsible design and development ethic, with a focus on higher performance facilities with lower or net-zero carbon operations costs.

A more recent trend, largely in the architectural sector, has started to investigate the actual carbon costs of construction. Even for high performance facilities, the carbon costs of construction were generally not accounted for. Academic and private practice thought leaders, from Bjorn Berge to Serge Salat, WRNS Architecture to KieranTimberlake, have started significant academic and design investigations into embodied carbon in construction, and have applied that information to lower the carbon footprint of construction. KieranTimberlake has developed a robust Revit Application "Tally," (KieranTimberlake, 2020) which accounts for embodied carbon and life cycle analysis and provides clear graphic outputs, using peer reviewed baseline data. This tool is rapidly becoming the standard tool for this kind of analysis, now with an application that can be purchased for subscription, and is accepted as a basis of documentation for LEED V4 Life Cycle Impact Reduction (KieranTimberlake, 2017).

Until recently, landscape design and planning disciplines had been tangential to these investigative trends, but in the last few years there has been a blossoming of research and tool development that brought their impacts into consideration (King, 2019). This had been an oversight, as only in the living landscape can we design and plan for economically viable carbon sinks, or carbon negative design, in the form of living materials that sequester carbon over their lifetime. In design rhetoric, carbon negative design through planting is often overstated or poorly understood, and the reality of landscape construction includes potentially massive carbon costs akin to architectural construction (McPherson and Simpson, 1999; Bernal et al., 2018; Stoffberg, 2016). However, planning and design decisions can significantly change the balance of this equation, with the landscape potentially being a net carbon sink (Conrad, 2020). In 2018, Pamela Conrad with CMG, in collaboration with Atelier 10, started a project with the Landscape Architecture Foundation (LAF) to apply existing research to practice. Her project led to developing the first detailed tool for evaluating carbon in the built landscape, the Pathfinder tool (Conrad, 2020).

We found the existing tools excellent for detailed design phases, applied to Revit models or with projects with accurate comprehensive cost estimates. However, we realized that we needed a tool for integrating architecture and landscape design data into an overall planning tool, enabling rapid iteration that would

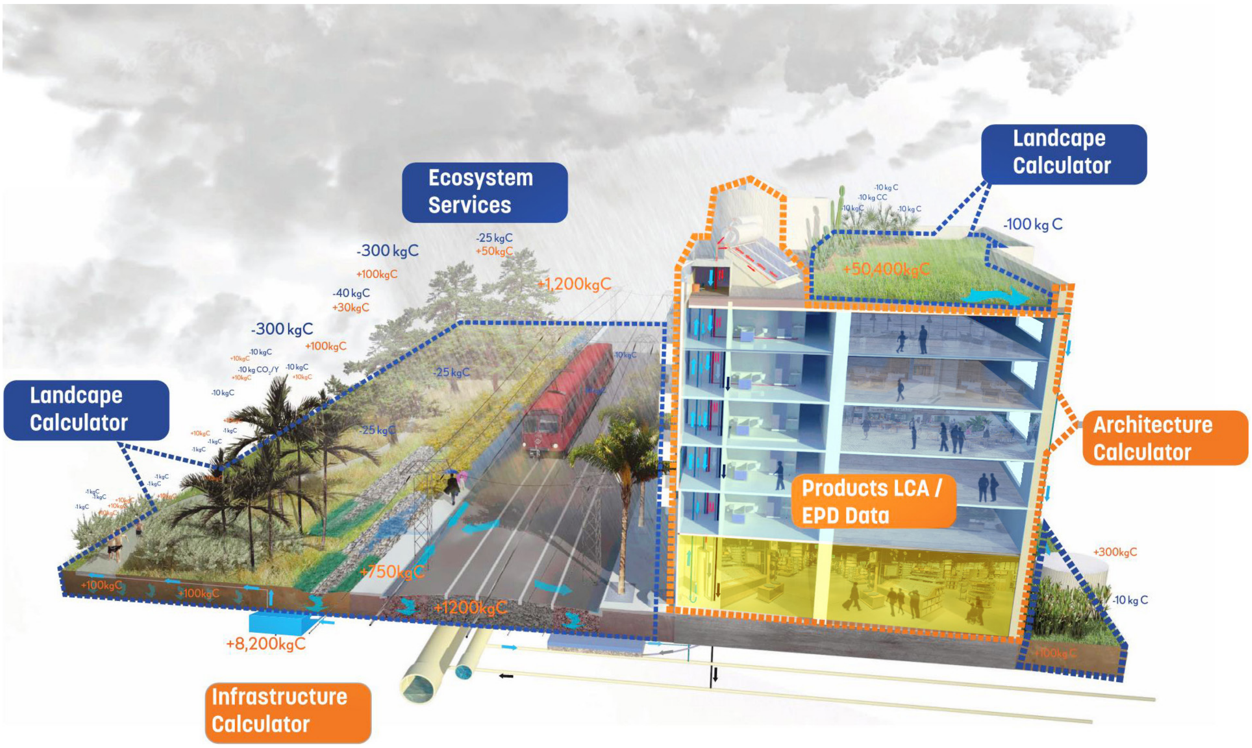


Figure 2:

A range of tools and calculators covering the built environment but divided by discipline.

allow designers to efficiently use it to inform early design processes; a tool for early sketches which brought architecture and landscape together, informed by civil engineering and ecology. This need led to the development of this literature review and the creation of the Carbon Conscience tool. This research was supported by an internal Sasaki Associates research grant.

To develop Carbon Conscience, our team first engaged in a broad literature and existing platform review, testing existing tools, comparing LCA certification programs, and compiling existing peer reviewed data sets on carbon emissions, storage, and sequestration. As part of our research, we applied existing carbon calculators to all or portions of a common project, Bonnet Springs Park, with which members of our research team were familiar from their role in design and construction administration processes. This project included a number of buildings, restoration ecology, and active park space, making it suitable to test methods that reached across design disciplines. To read about our conclusions for existing tools and platforms, please see: Appendix A: Additional Carbon Calculators and LCAs Reviews and Resource Recommendations.   To see our full bibliography for all sources cited and used in the development of Carbon Conscience, please see the Bibliography posted under the methodology portion of the website. Within the scope of our research, we only found very high level estimates of carbon per unit area within the built environment, and a range of approaches for evaluating the ecosystem services associated with carbon.

All carbon calculators are essentially tools that input material takeoffs, multiply them by their carbon costs, and sum the carbons costs for all materials. In the case of Pathfinder, in addition to costs, carbon sequestered is also accounted for in the case of living materials that will store carbon as they grow. For Carbon Conscience, we wanted to bring together embodied carbon, carbon sequestered, and carbon stored, which we considered the key carbon impacts, positive and negative, associated with construction.

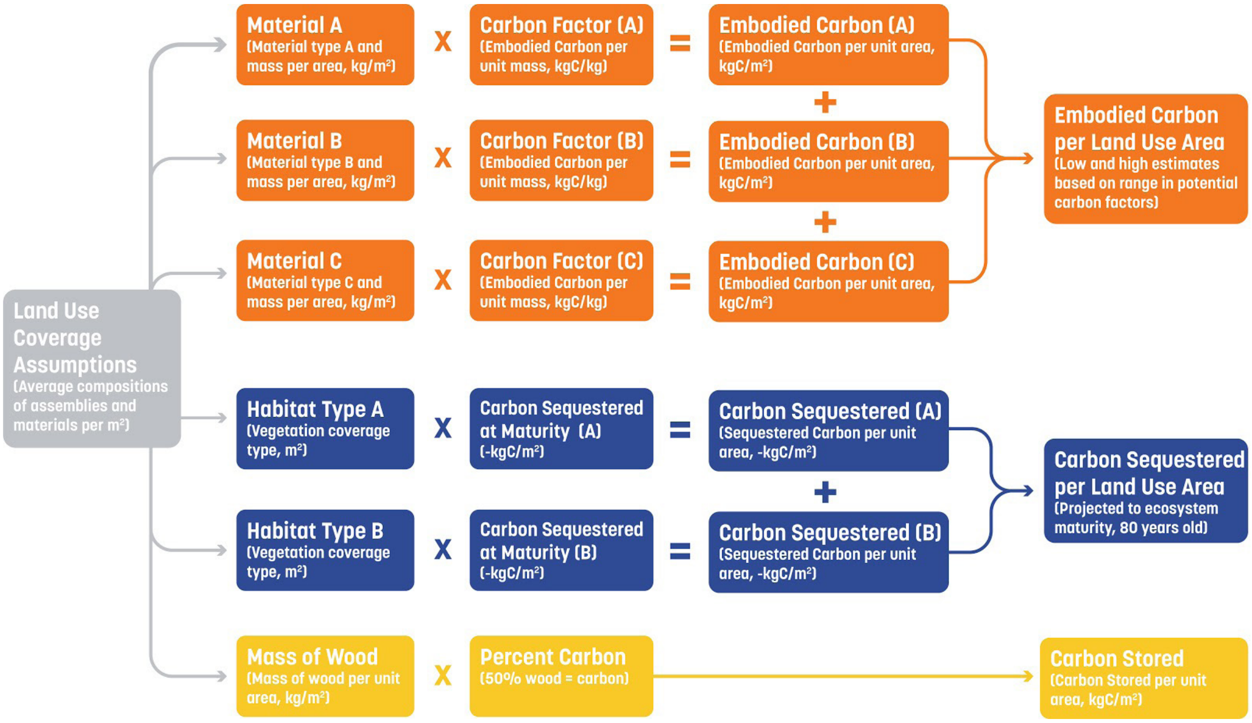


Figure 3:

Simplified graphic showing carbon calculator process within Carbon Conscience.

Our research reinforced our early perception that there is a gap in existing tools for early design phases and interdisciplinary projects. To encompass the types of materials and inputs that would be relevant across disciplines and specifically from a planning and urban design perspective, we needed to develop a tool that projected embodied carbon per unit area of land use so that there was an even unit of measurement across diverse types of intervention. To do so required developing a database of land uses, the expected material masses for each unit area (taken from larger land use coverages and averaged per square meter) of that land use, and the types of work performed in constructing that land use. The calculator could then sum those inputs to estimate carbon impacts per unit area.

In assigning embodied carbon costs to various types of land use, we found that depending on the data source, there is a wide margin in estimated carbon factors for any given material, or carbon sequestration for any given ecosystem type, in some cases up to 50% of the mean value of the variables. This made us realize that for this tool to be accurate, it would be unrealistic to estimate a precise carbon value for a designed project; rather, it could supply projected carbon metrics, document all assumptions and citations used in supplying those metrics, and encourage designers to compare design options based on a common reference. With that in mind, we intentionally targeted our dataset to bring together existing architectural, landscape, and ecological data with a square meter resolution. The ideal project for this scale would be at a campus or neighborhood master plan scale, including multiple landscape and architectural land uses, but we also strove to include enough specificity for a building or site-scale concept design.

Methodology

The Carbon Conscience application uses a similar methodology for estimating a project's carbon impacts as other carbon calculators – by multiplying the mass of included materials by carbon emission, sequestration, or storage factors, and summing the aggregated results for a given project. The value of the Carbon Conscience tool is the application of estimated carbon impacts per given land use, rather than relying on precise takeoff measurements for specific materials. This fundamental difference from other available tools requires Carbon Conscience to use a detailed set of assumptions per land use type to project anticipated carbon impacts per unit area, especially because references and studies that had estimated a precise carbon value for land use types were not always available.

A valuation decision was made early in the development of this tool to focus exclusively on embodied carbon costs, carbon sequestration at maturity, and carbon stored per land use area, rather than considering the myriad decisions that would influence a project's operations energy usage and carbon cost. These key factors together summarize the impact of the constructed environment, and could be considered complementary and supplementary to energy modeling and designing for net-zero environments from an operations perspective. While we omitted operations and maintenance carbon costs, focusing on embodied carbon alone would ignore the ecological contribution of the landscape in terms of carbon sequestered by planted material and carbon stored in existing ecosystems; therefore, we included carbon stored and sequestered in the Carbon Conscience calculations. Together, these variables represent the impact of a constructed project, architecturally and in landscape, in terms of carbon emissions. While embodied carbon emissions and carbon stored are largely realized by the completion of construction, carbon sequestered is an estimate of net carbon sequestered per land use type projected to maturity. Carbon sequestration, as a variable or factor per habitat type, turned out to be the singularly most variable projection within our research, and for the purposes of this study we developed a set of specific assumptions pulling together a range of references to make estimates that are proportionally relative and matching in units across different vegetative coverage types. To tie these various studies, terms, and professional disciplines together, we needed to limit this research and development of the database within a set of baseline assumptions. The baseline assumptions apply to all materials and assembly estimates included in this first version of the complete database.

- We assume materials are sourced and fabricated following industry typical practices as of 2019.
- We assume energy used to fabricate materials, unless otherwise indicated, is solely from non-renewable resources. This is the most likely scenario for work within North America. In countries with a high percentage of renewable energy sources, we have found EPDs reflect a corresponding drop of almost 50% for materials such as timber, 25% for materials such as concretes and metals.
- We assume one replacement cycle for most materials. The exception would be materials that can be reused for 80 years, such as stone or metals that develop a superficial patina.
- We assume materials are transported to the site using ground truck transportation, and provide a range of baseline distance estimates depending on material or assembly.
- We include factors for installation of materials on site or movement of materials on site assuming large diesel-fueled construction vehicles.
- Our landscape data set does not exhaustively account for field installation methods. Carbon costs associated with field welding, fastening, or hand-craftsmanship are not accounted for.
- Our landscape data set includes baseline values for irrigation, site drainage and

lighting, but not any trunk-line infrastructure utilities, telecom, or large scale infrastructure elements. For moderate scale sand filters or larger catch basins or concrete cisterns, we recommend users use the CIP concrete wall typology as a placeholder.

- For Carbon Stored and Sequestered, we covert the kgC to global warming equivalent, $kgCO_2$. (One Kg of carbon equals 44/12 = 11/3 = 3.67 Kg of carbon dioxide.)
- Our architectural data set is taken from whole building analysis, averaged across a range of buildings; there are variations in comprehensiveness and methodology for each building data point.

These assumptions per land use category are discussed further down in this paper; however, before we could develop those assumptions, we also needed to add more specificity to the working definitions for our key variables, as we also found a wide range of interpretation for these variables across our literature review.

To provide a standard understanding to develop our metrics, we have used the following definitions: LCA:

- **Life-Cycle-Assessment:** A material or product data sheet that estimates a variety of impacts for that material on the environment over the material life span, including Global Warming Potential (GWP) measured in kilograms of carbon emissions equivalent.
- **Carbon Emissions:** Carbon dioxide emitted through an activity or process, such as material extraction, fabrication, transportation and assembly, and possible demolition.
- **Carbon Equivalent:** The equivalent mass of carbon dioxide in terms of GWP (global warming potential). This simplifies emissions of various greenhouse gases into one metric, and is the basis for most LCA estimates of carbon impact of materials.
- **Carbon Factor:** A multiplier that refers to emissions per mass of a given material. The standard unit used is kgC/kg (Kilograms of carbon dioxide emissions equivalent per kilograms of material).
- **Embodied Carbon:** Estimate of the probable carbon emission from a material or product's sourcing, fabrication, transport, and installation on a site. The standard unit used in this data set is kgCO2e (Kilograms of carbon dioxide emissions equivalent) (abbreviated in our tables as kgC).
- **Carbon Stored:** The mass of carbon locked up within building materials, vegetation, or soils that is not readily off-gassed into the atmosphere. For the purposes of this project, we counted carbon stored for at least 20 years. The standard unit used in this data set is kgC (Kilograms of Carbon stored) and kgCO2e (Equivalent Kilograms of Carbon dioxide).
- **Land Use:** A description of the coverage of a piece of land; for example, "Restored Wetland", "2- Story Single Family Residence", and "Low-Intensity Concrete Hardscape" are all different land uses. This tool focuses primarily on proposed land use, with the exception of preserved existing-to-remain habitats.
- **Carbon Sequestration:** The active storing of carbon from the atmosphere into vegetation or soils.
- **Projected Carbon Sequestered:** The amount of carbon actively stored or fixed from the atmosphere in vegetation or soils, after construction. For the purposes of this project, we used the net sequestration of carbon within a given habitat or vegetation coverage in living and non-living biomass, accounting for respiration and decay. The standard rate of sequestration used in this data set is kgC/m2/yr (Kilograms of Carbon dioxide sequestered per square meter per year). Because of the variable sequestration rates over the growth of vegetation and decline or balancing with net respiration and decay (depending on ecosystem) at maturity (Pugh et al., 2019; Radford, 2019), we project carbon sequestered within 80 years of project installation (80 years as the standard estimate of forest maturity by the United States Forest Service) (USFS, 2003). The standard unit for projected carbon sequestered in this tool is kgC/m2 and kgCO2e (Equivalent Kilograms of Carbon dioxide).

We developed a tiered approach to land use mapping, starting by splitting between Landscape and Architecture typologies, then by high-level land use or program categories, then subdividing into finer designations. The high-level categories for Landscape include Existing to Remain, Demolition and Site Preparation, Hardscape, and Softscape. The equivalents within Architecture are defined by the building program, described more below. Each of these categories drew upon very different references and data sets to bring together carbon estimates on a per-unit land area basis. The following page shows the hierarchy of land uses and composition of the Carbon Conscience database.

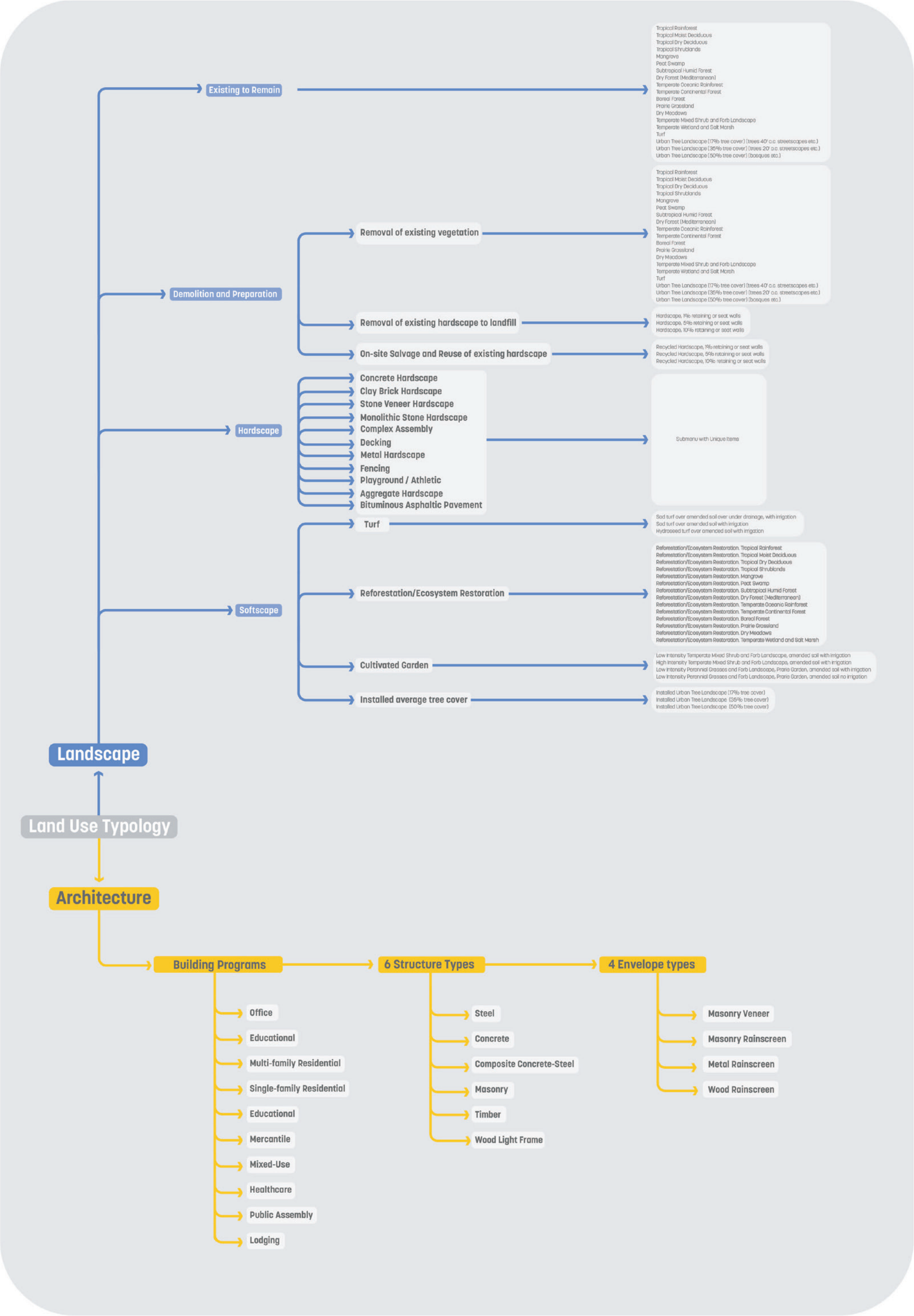


Figure 4:

Land use hierarchy and composition within Carbon Conscience calculator.

The Architecture land use typology was broken down into programs based on building use. These programs included Office, Educational, Multi-family Residential, Single-family Residential, Mercantile, Mixed-Use, Healthcare, Public Assembly, and Lodging. Each program had a different profile, developed through a combination of the data accessible through the Carbon Leadership Forum "Embodied Carbon Benchmark Study," (CLF, 2017), the Database of Embodied Quantity Outputs "deQo" by MIT (deQo, 2014), and Kierran Timberlake's "Tally" platform applied to representative Revit models (Kierran Timberlake, 2020). The goal with combining these sources was to provide Carbon Conscience users the option to delve into greater detail in additional tiers of information by specifying the structural system and façade system. Each of these building land uses was developed through evaluations of complete buildings, and industry databases were averaged and divided by stories to develop high and low estimates of embodied carbon and carbon stored for each building element per square meter per story.

All low and high estimates per material, structure, or program reflect a range found in cited literature, reference projects, or ranges within specifications of a given material. As the Carbon Conscience application is intended to be a living tool and document, the values for given materials are being iteratively evaluated given new information.

To reference a comprehensive land use data set and assembly assumptions for each land use, please refer to Table 1: Landscape land use Carbon Data Set and Table 2: Architecture land use Carbon Data Set.

Landscape Land Uses

For the Landscape typology, we made detailed assumptions of the average composition of a particular land use per square meter, either taken from literature or informed by the review of approximately a dozen active projects with our office. We then isolated each element or assembly within that land use type, and provided high and low estimates of embodied carbon, net anticipated carbon sequestered at maturity, and carbon stored for that element per square meter. These estimates were generated from an aggregated carbon costs materials data table, an aggregated carbon sequestration at maturity data table, and an estimated carbon stored calculation. These can be reviewed in Table 3: Landscape Materials and Assemblies Data Set, Table 4: Landscape Materials Carbon Costs Data Set, and Table 5: Landscape Carbon Sequestration Data Set.

Existing to Remain category land uses capture the carbon to be sequestered over an estimated 80 years for preserved-in-place ecosystems. Demolition and Site Preparation land uses includes the carbon costs of removal and the release of stored carbon in demolished existing ecosystems (both disturbed soils and vegetation), earthwork and site preparation, and demolition of existing hardscape elements. Hardscape category land uses include a wide range of potential built landscape surface coverage, from concrete buildings to playgrounds and decking systems. Softscape category land uses include all planted conditions, from turf and gardens to various ecological restoration plantings. Detailed methods are provided below for each land use category.

Existing to Remain Landscape

The Existing to Remain land use category is intended to capture vegetated landscape cover that could contribute to the net carbon stored or sequestered for a given project. This recognizes the value of preserving existing living systems from a carbon perspective. Hardscapes are not included within the Existing to Remain category as they have negligible impact on carbon emissions, sequestration, or storage and can be effectively treated by excluding them from the scope of work. The existing to remain land uses within Carbon Conscience are categorized as different mature ecosystem types or horticultural landscapes. Based on sample calculations that we performed, it was assumed that any construction costs associated with preservation in place, such as tree protection or temporary fencing, are negligible when reviewed at campus or neighborhood scales. To review the carbon costs for specific materials and assemblies and associated citations, please refer to Table 3: Landscape Materials and Assemblies Data Set and Table 4: Landscape Materials Carbon Costs Data Set.

A key variable needed for this land use category was an estimate of the carbon stored within various habitats. Across vegetation types, approximately 50% of dry biomass is carbon (Schlesinger, 1991). Methods for estimating dry biomass per land cover type range widely; for this study we relied on estimates from forest ecology and management journals, and narrowed in on a range of broad categories with global data sets per ecosystem as used and cited by the UN Food and Agriculture Organization (UN FAO, 2001), including data from Proulx et al.(2015), Easdale et al.(2019), and Pan et al. (2016). While this provides a basis for carbon stored in living biomass, in some cases these estimates focus only on aboveground estimates. To provide a carbon stored dataset for the Existing to Remain category, we wanted to account for both the carbon stored within the living biomass and the non-living biomass locked within the soil. For below ground, we were able to find generic multipliers used in several studies, such as an empirical study by Jianjun et al. that found that grasslands and shrublands had 2 to 3 times their living aboveground biomass in their below-ground root structures (2019), or the estimate from Easdale et al. that in forests, the equivalent dried biomass of root systems approximated 30 percent of the measured aboveground biomass in a range of forest types (2019). Taken together, we assumed a 3 times multiplier of aboveground biomass estimates for prairie and wetland vegetation, 2 times for dry grasslands, and a 1.3 multiplier for forests or tree coverage, to account for both aboveground and below-ground living biomass.

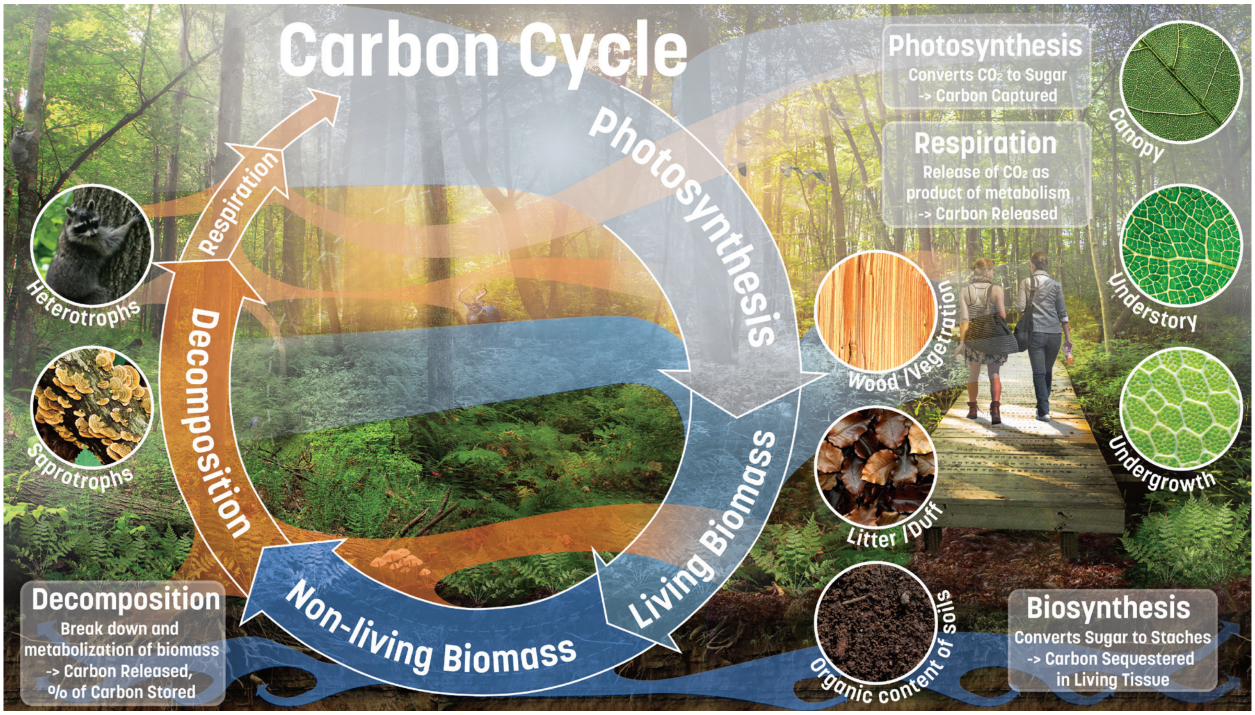


Figure 5:

Carbon Cycle Concept Diagram.

The estimate of non-living biomass contained below-ground in soils, humus, and duff is characterized by numerous complex studies that take into account historic land use, soil structure, soil formation, and land coverage. Many of these studies included in the literature review were developed from an agricultural perspective, and all tend to be highly site or system specific and difficult to extrapolate to broad land use categories. Ultimately, we made a projection based on a few soil types and informed by the net climatic impact on soil carbon composition. In general, there is an inversely proportional relationship between the carbon stored within soil and average climate temperature; in warmer climates the carbon within the soils and non-living biomass decays faster (Keith et al., 2008). In tropical and subtropical climates, Keith et al. found the carbon in soils to be less than 15% of the total living above and below ground biomass, while in boreal climates it can be 300% or more of the living biomass (2008). In grasslands, non-living biomass has been estimated to be on average 80% of the total biomass (Hofstede et al., 1995). Certain ecosystems, specifically peat bogs, mangroves, salt marshes, and temperate wetlands, which all have anaerobic soil conditions, can effectively store a substantial proportion of the annual carbon sequestered in their soils (Easdale et al. 2019; Asada et al., 2005). In the case of peat bogs, almost all biomass grown is ultimately fixed in the peat (Asada et al., 2005; Doughty et al., 2015).

Combining these factors (temperature, above and below ground living biomass, and non-living biomass) produced our estimates for the carbon stored per ecosystem type, each combining the dried living biomass with the non-living, and dividing in half to predict the stored carbon. Several key studies were used to provide carbon estimates by area for anthropogenic plant-based landscapes such as turf grasses (Springer, 2009; Selhorst, 2013; and Zirkle et al., 2011), urban tree and garden landscapes (Nowak et al., 2013; Nowak and Crane, 2001; McPherson & Simpson, 1999; Kooten et al., 2015).

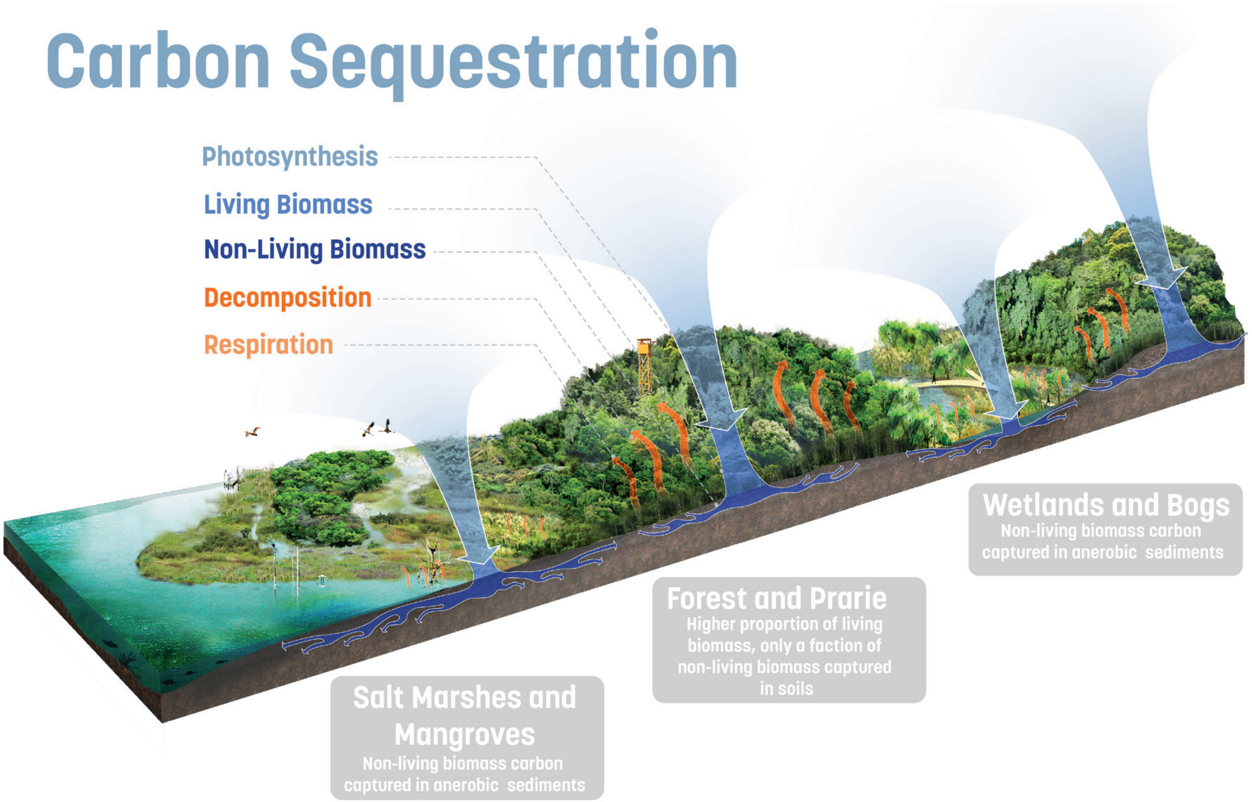


Figure 6:

Carbon Sequestration Concept Diagram - contrasting wetlands and forest, for living biomass and carbon storage.

Carbon sequestration tends to decline as systems approach maturity (Radford, 2019; Wohllenben, 2016); we therefore approached projected sequestration rates by selecting a finite period of projected growth, and from two perspectives which we found commonly used in related literature. The first was accounting for the annual average sequestration for a land cover type and multiplying that for the projected years of growth, using a mean sequestration rate that would account for the fast growing years and slower growth years (Nowak and Crane, 2001). The second was using the referenced fully established ecosystem as an upper limit of projected sequestered and stored carbon (Luyssaert et al., 2008). The results from these two approaches were unsurprisingly different, with substantially higher estimates of carbon sequestration projected over 80 years for net carbon stored with the annual approach versus the mature reference ecosystem approach; however, when we factored in probable decomposition rates derived from non-living biomass projections, that brought the projections much closer. By comparing these various sources and cross referencing with similarly structured ecosystems as a checkpoint (shrubby woodlands compared to gardens, meadows compared to lawns, etc.), we were able to compile the carbon stored and carbon sequestration data set, which can be reviewed in Table 5: Landscape Carbon Sequestration Data Set, along with related citations per land use.

Given this research and compilation, we still had to make a few key assumptions to develop this model. We first split habitat or vegetation coverage types between tropical/subtropical, temperate, and boreal climates. We assumed mature tropical and subtropical ecosystems are static in terms of sequestration (i.e. rate of sequestration equals combined rates of respiration and decomposition) even as they stored large reserves of carbon. We assume mature temperate vegetation types as static from a living biomass perspective, but net sequestering 20-60% of their annual biomass growth in non-living biomass or soils, depending on specific vegetation type. We also assumed a one-to-one storage of carbon for ecosystems with anaerobic soils to store non-living biomass, such as peat bogs, mangroves, and wetlands. We assumed a high level of sequestered carbon in boreal and tundra ecosystems, at 70-80% of annual accumulated biomass based on (Keith et al., 2008). Note that these assumptions and accumulated metrics and literature review do not account for carbon emissions from various landscapes as resulting from climate change, such as peat decay or methane releases from permafrost thawing.

Through this approach, we aimed to account for some common errors that result in significant over-estimates in carbon sequestration, such as the erroneous assumption of infinite growth and associated sequestration (which only closely relates to ecosystems with anaerobic soils such as wetlands and bogs), the application of a static linear growth rate to planting materials, or variability in stem density or leaf area index for a given vegetation cover. By considering those potential biases, we are intentional in developing a conservative model tied as closely as we can to existing literature, and will begin seeking peer feedback in 2021. While our assumptions are informed by our literature review, they would benefit from further sources and field research to refine these relative factors for comparing land uses.

Demolition and Site Preparation

The Demolition and Site Preparation land uses are intended to be used as a sketch tool for landscape architects to help them prioritize what kind of landscapes benefit from preservation from a carbon perspective. This category uses the carbon stored data set for vegetative land uses as defined in the Existing to Remain description above (reference it here, parenthetically), and assumes that all organic carbon is released from the site in the act of demolition and site preparation. In reality, this would only apply if the existing vegetation is burned or composted, and if soils are disturbed enough to release existing carbon reserves. The impacts of demolition of existing vegetation can be partially ameliorated by careful harvesting of wood and non-wood forest products and the preservation of existing soil structure, mulching of vegetation, and storage of any charred wood within soils (Marinelli, 2019). Given the site specificity and nuisance of these methods, our default assumption is complete removal of existing carbon and significant regrading of soils. We assumed an average 0.5 meter depth of regrading globally per square meter, clearing and grubbing, and site protection. We assumed mulching of all existing material, and the removal of all waste to a facility within 50 km through ground transportation. For all ground transportation, we used the EPA and DOE average estimate of 0.200 kgC/ton-mile (0.0003344 kgC/kg-km) (EPA, 2020; DOE, 2020). For equipment emissions per unit volume or mass moved, we used a variety of equipment technical manuals, with a bias toward larger scale equipment commonly used on sites larger than 1 acre (Lawn and Order, 2020, Product Information; Hajji et al., 2017; Hajji et al., (2) 2017; Jassim et al., 2017; General Rental Center, 2020, Product Information; Downeaster, 2020, Product Information).

For hardscape demolition, we assumed the same site preparation and earthwork costs, but also included the transportation costs of removal of waste materials to an off-site facility within 50 km of the site. For salvage materials, the Carbon Conscience calculator accounts for the carbon savings by adding the carbon costs of large in-place-concrete crushers for processing hardscapes into aggregate base, but also subtracts the mining, fabrication, and transportation costs for an equal volume of import. This results in a net carbon savings, from -6.54 kgC/m2 to -1.18 kgC/m2, in comparison to removing waste to a disposal facility and importing the equivalent volume in aggregate. Together, this produces the results for Demolition and Site Preparation shown in Table 1: Landscape Land Use Carbon Data Set.

Hardscape

The methodology for the Hardscape category follows the model set by contemporary LCAs such as Athena and calculators such as Tally. Each land use was described as a composition of elements, (see "Assumptions: Assembly Composition" column of Table 1: Landscape land use Carbon Data Set). Each of these elements has their own embodied carbon emissions and storage analysis shared in Table 3: Landscape Materials and Assemblies Data Set. To develop that dataset, we combined references of a range of primary sources, literature surveys, and already developed LCA resources to define the low and high carbon factors for each material. This data set is available in Table 4: Landscape Materials Carbon Costs Data Set. Where relevant, we annotated the cause of the variation in low and high estimated carbon factors in the "Range Notes" column of the table. Material densities were primarily cited from the Engineering Toolbox website, https://www.engineeringtoolbox.com. The citations associated for specific materials are found within the table. For transportation costs for materials, we generally assumed very local materials, such as base aggregate, would be sourced within 50 km of the project; materials requiring more centralized processing facilities, such as concrete, within 160 km; and specialty materials, such as playground equipment, within 800 km. The one extreme exemption to this approach was internationally sourced hardwood lumber, which we included at 3,000 km. We kept all transportation metrics as ground transportation to simplify the analysis and default to typical practice in many North American communities.

Softscape

The approach for developing Softscape category carbon factors builds on the research and dataset described in the 'Existing to Remain' section above for carbon stored and sequestered for each element. A key difference is that in this case, we assumed the full living biomass of the plantings once matured was net sequestered, in addition to the proportion accumulated in non-living biomass. This information is compiled in Table 6: Landscape Carbon Sequestration Data Set, and is built on the same approach and citations as the existing to remain metrics. In addition to the carbon stored and sequestered, softscape land uses also account for installation and nursery industry carbon costs, see tables for specific citations used per material. Existing references were species and method specific, so we used available values as a basis for generalizations. In addition, many of these studies already accounted for the carbon sequestered during the growth of the planting material at the nursery, so the values used in this data set reflect anticipated net carbon values for once the material is ready for installation. In addition to 'fabrication' or farming costs, we included transportation costs for materials, assuming material sourced within 50 km of the site. The summary of costs associated with softscape material production is found in Table 4: Landscape Materials Carbon Costs Data Set.

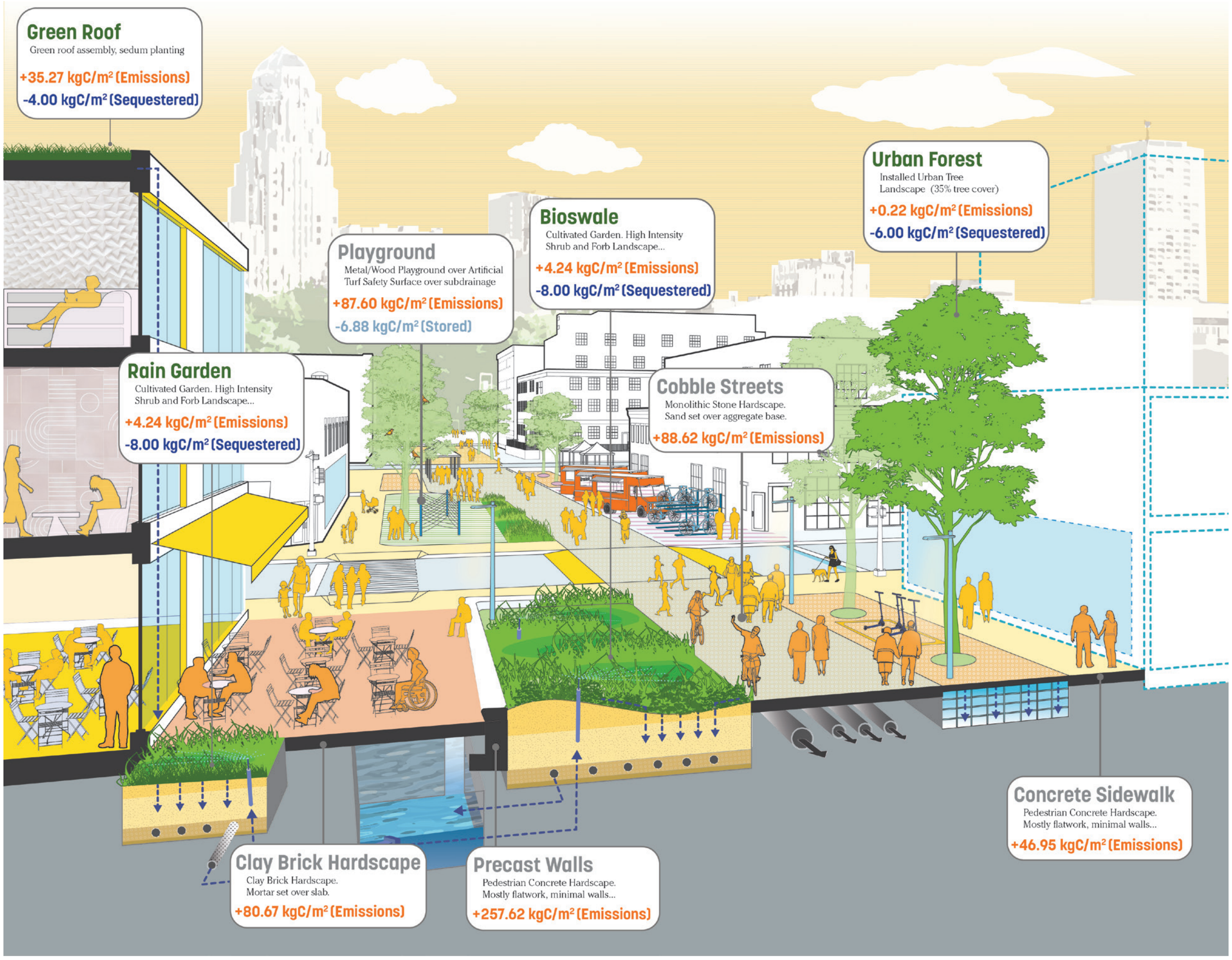


Figure 7:

Concept diagram of mapping landscape typology land uses, comparing hardscape to softscape categories, within a project focused on introducing green infrastructure and pedestrian environments into lower traffic streets and alleys.

Architecture Land Uses

The embodied carbon in architecture varies in accordance with a broad range of variables. Many existing embodied carbon calculators for buildings, such as One-Click LCA and Tally, rely on highly detailed building models at the Design Development or Contract Documents level. For the purpose of this Carbon Conscience planning-level calculator, we selected a few key variables that have a major impact on embodied carbon: the building program, the structural system, and the facade material, multiplied by the building area. Using a range of embodied carbon values for each of these key variables derived from recent databases, we can determine a planning-level estimate of embodied carbon for each architectural land use.

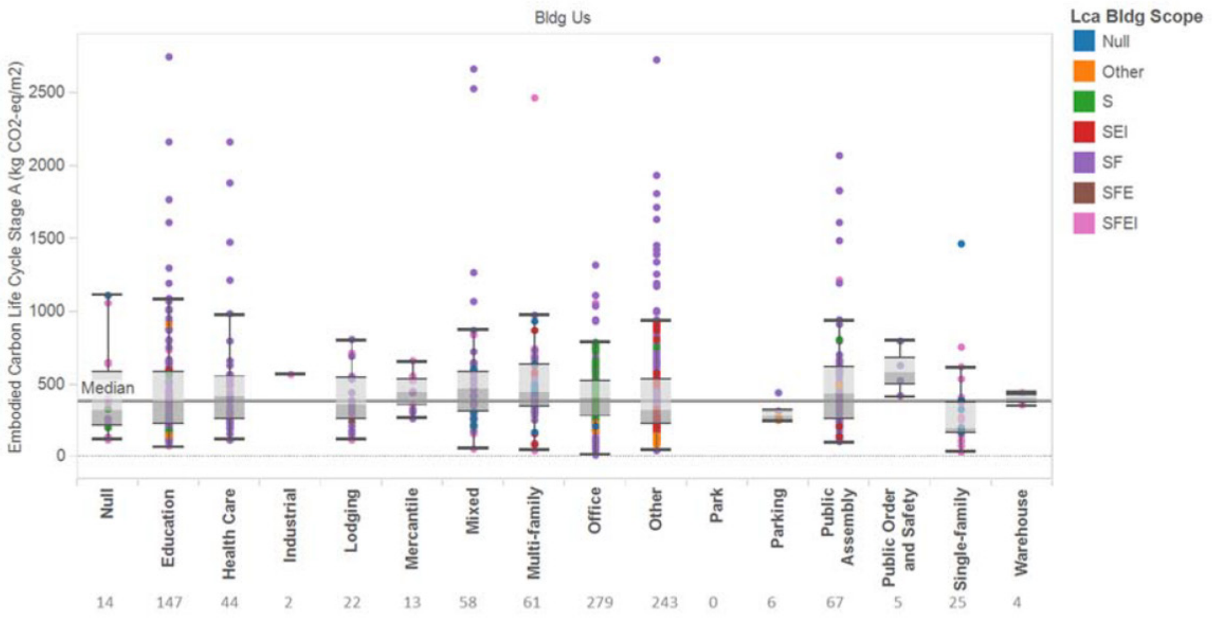


Figure 8:

Carbon Leadership Forum benchmark study, used as part of the development for the Carbon Conscience architectural dataset, (CLF, 2017).

Building Program

For architecture land uses, start by selecting the proposed building program. Each has a unique embodied carbon estimate sourced from the Carbon Leadership Forum (CLF) Embodied Carbon Database (CLF, 2017). This database is the largest of its kind for embodied carbon reporting, consisting of calculations of over 1,000 built projects across a broad range of program types. Filtered by program, ranges were reported from the database using the lower and upper quartile values for nine program types: Office, Educational, Multi-family Residential, Single-Family Residential, Mercantile, Mixed-Use, Healthcare, Public Assembly, and Lodging and include the full building scope (foundations, structure, enclosure, and interiors).

These initial estimates can then be refined by the user by assigning a structural system and facade type to the building, as additional optional tiers described below.

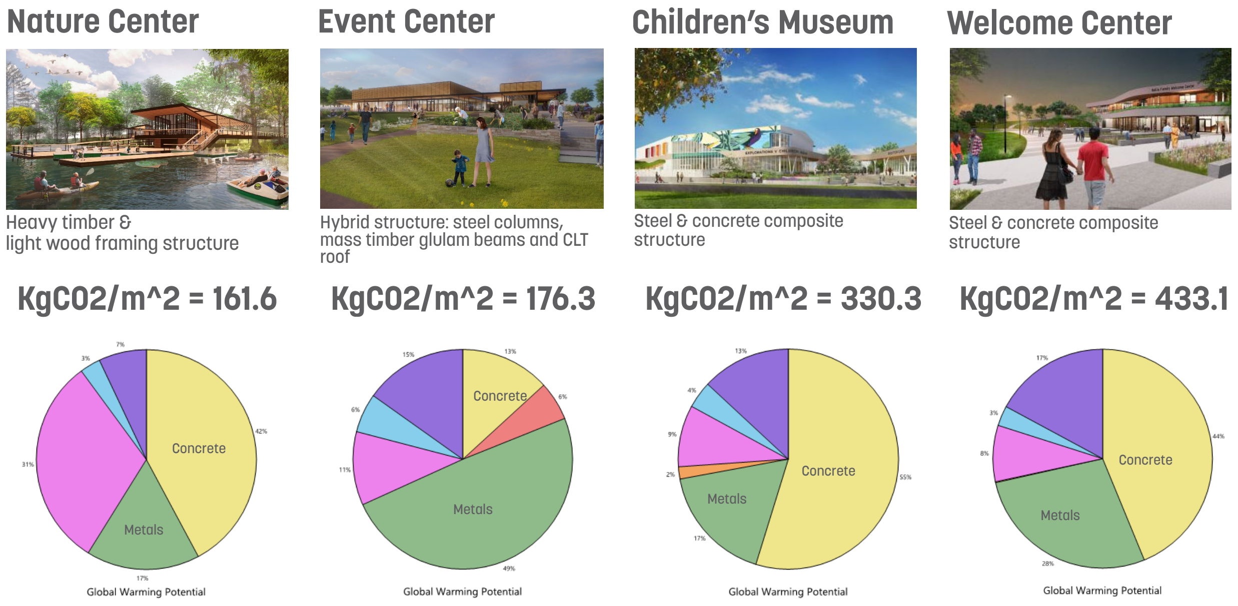


Figure 9:

Comparing carbon impacts of four buildings at Bonnet Springs Park, comparing three structural systems as well as various envelope and roof types with Tally, architecture by Sasaki, Tally by KieranTimberlake.

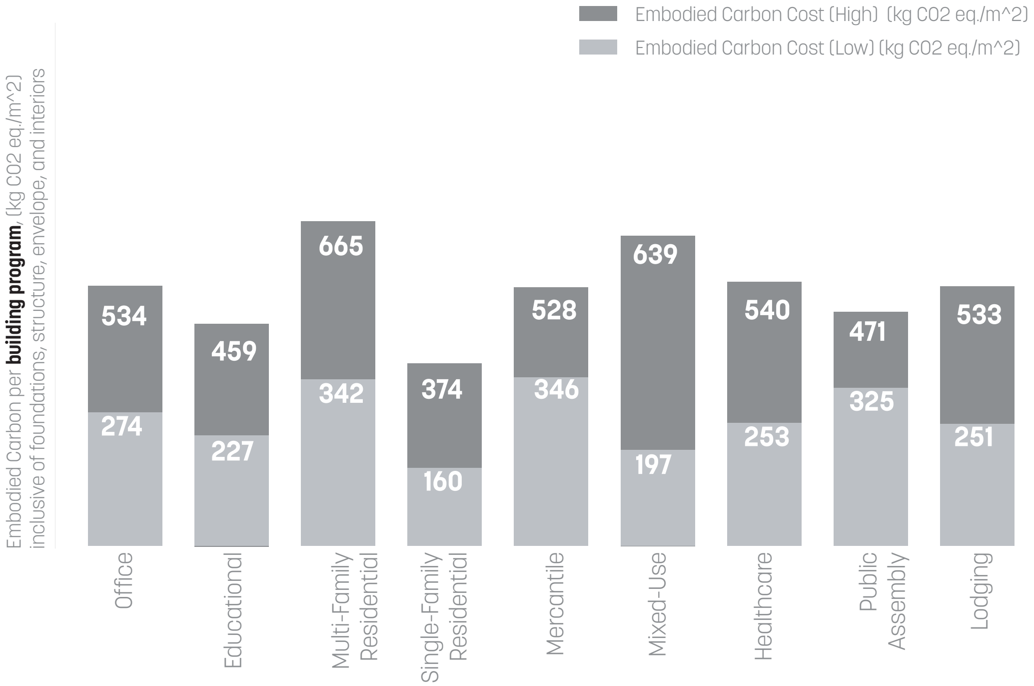


Figure 10:

Comparing carbon impacts by building program land use, per floor above ground, based on the Carbon Leadership Forum Benchmark Study, (CLF, 2017).

Structural System

The structural system of a building can account for approximately 75 to a building's total embodied carbon, according to Sasaki's recent studies. Other studies have corroborated these findings, and posited that up to 80% of embodied carbon emissions are from building structure (Paula Melton, BuildingGreen; Architecture 2030). At the early planning stages of a project, the composition of the structural system is not always known. However, once a structural system can be determined, it can be very helpful in refining the embodied carbon estimate of a project. For our calculator, we have defined six structural categories: concrete frame, steel frame, concrete-steel composite, masonry, mass timber or wood light frame.

To estimate embodied carbon from structure, estimates from the CLF database were refined using the factors derived from the Database of Embodied Quantity Outputs, (deQo, 2020). The deQo database contains data on both the mass of the structural material of five types of structural systems and their corresponding embodied carbon/building area (kgCO2e/m2), providing ranges sourced from over 500 built projects.

To represent the structural contribution of embodied carbon to the building and refine the range from the CLF database (inclusive of foundations, superstructure, envelope and finishes), the range as defined by the upper and lower quartiles of each given structural system was used. Factors were developed for each structural system based on each category's relationship to the averaged mean value of all structural categories. To refine the CLF database range, this structural factor for each category was multiplied by the original ranges of the CLF data for each program type, to arrive at a more targeted range, more representative of each structural system's embodied carbon. To represent the significance of the structural systems' impacts on a building's embodied carbon, this targeted range modified from the CLF data was applied to 75% of the building's total embodied carbon calculation, with the remaining 25% to be a modifier based on the buildings' envelope systems.

Concrete

Concrete is the most consumed building material; it is durable and widely-used in construction across a broad range of project scales, program types, and geographic locations. Given its inherent non-combustibility, not requiring any additional applied fireproofing product, concrete is an ideal choice for tall buildings and has preferential treatment in many building codes, typically allowable for buildings of unlimited height for most program use groups (ICC, 2020), giving it a clear advantage over other structural systems for high-rise applications. It is also best suited for below-grade stories and foundations, with its solidity making it an ideal substrate for most waterproofing systems.

However, concrete is extremely carbon-intensive, with the production of cement being the main contributor to its Global Warming Potential. Cement is the highest embodied carbon masonry hardscape material due to the carbon costs of its fabrication, requiring high energy inputs to produce clinker through sintering, and emitting CO2 as a chemical byproduct of its formation. Cement has been estimated to account for approximately 8% of the world's carbon emissions (Lehne and Preston, 2018). Per the deQo database, the values for embodied carbon for concrete structures ranged from 278-436 kgCO2e/m2 , (inclusive of reinforcing steel,) placing them together with steel among the most carbon-intensive structural systems. (De Wolf, 2014).

There is a substantial ongoing effort in the construction industry to mitigate the embodied carbon emissions of concrete through a range of strategies, including the reduction of the quantity of cement in concrete mixes and its replacement with supplementary cementing materials (SCM's) such as slag or fly ash, as well as carbon capture technologies (Logan, 2020). Since various forms of concrete are prevalent in many building components (floor slabs, foundations, and below-grade stories,) it is important that designers employ these strategies to mitigate the embodied carbon impacts of concrete.

Steel

Steel structures are also well-suited to a broad range of building programs and scales. When protected by either applied fireproofing or enclosed by fire-resistance-rated assemblies (most often gypsum wallboard,) it is considered a Type I structural system and can be used on buildings of almost any size and program use group (ICC, 2020). Per the deQo database, the values for embodied carbon for steel structures ranged from 233-533 kgCO2e/m2, a broader range than concrete, with the upper limit being the highest of all structural systems evaluated.

The embodied carbon impacts of structural steel are most affected by the recycled content of the steel itself, and therefore, by the availability of scrap steel material. While recovery rates are high, globally, the amount of recycled steel used in structural steel production is currently approximately only 26% of total global steel production, (BIR, 2020) and primary steel requires a more carbon-intensive production method using a basic oxygen furnace, which requires nearly three times as much energy to produce as recycled steel produced in an electric arc furnace (De Wolf, 2017). Effective strategies for reducing the embodied carbon of structural steel include sourcing steel from facilities utilizing recycled scrap materials and produced with electric blast furnaces, and designing for maximum material efficiency.

Concrete-Steel Composite

Composite concrete-steel structures encompass a range of different configurations, but all utilize the unique advantages of concrete and steel to achieve material efficiencies, as well as a reduced structural depth for horizontal members. This can be an advantage for high-rise projects where floor-to-floor heights are especially critical. Per the deQo database, the values for embodied carbon for steel structures ranged from 245-472 kgCO2e/m2, with the uppermost range being lower than that of both concrete and steel systems (De Wolf, 2017). Design strategies for minimizing embodied carbon of this structural system include the use of hollow-core precast planks to minimize the volume of concrete required for floor slabs.

Masonry

Masonry, along with timber, is a relatively low-embodied carbon structural system, with its range in deQo being 266-311 kgCO2e/m2 (De Wolf, 2017). Applications of masonry structural systems are generally limited to six stories in model building codes when the exterior walls are masonry (ICC, 2020), and are limited accordingly in the CarbonConscience calculator.

The variability of the embodied carbon of masonry structures is due to two key factors. The first is the composition of the masonry units used (most often concrete masonry units (CMU), brick, or stone. When specifying CMU, the cement content of the masonry units itself, as well as that of the mortar binding the units together, is an important consideration. The second key factor when designing masonry structures is the complementary structural systems. While masonry is well-suited for vertical applications such as load-bearing walls, the horizontal elements of this system (beams and decking) are typically composed of wood, steel or reinforced concrete.

Mass Timber

Use of natural materials such as wood will have clear benefits in reducing embodied carbon in buildings. Timber sequesters carbon by transforming carbon dioxide in the atmosphere through photosynthesis. If timber is harvested from sustainably managed forests, a range of timber and lumber products are the lowest possible embodied carbon structural systems for buildings.

The use of mass timber has grown rapidly over the last decade, and is being employed in an expanding range of project types and scales. As continued laboratory testing and built projects have demonstrated its capabilities, it will be approved for use in the 2021 International Building Code for buildings up to 18 stories tall, when certain conditions are met to enhance the innate fire resistance rating of the timber structure (Bland, 2019).

By using cross-laminated timber (CLT) for floor and roof slabs and exterior walls, and glulam beams and columns, entire structural systems (save foundations) can be constructed of mass timber elements that would otherwise require substantial amounts of concrete and steel. Many applications of mass timber construction allow these elements to be exposed to view due to their inherent fire resistance properties, allowing for a material and embodied carbon efficiency by avoiding additional finishes and enclosures.

Per the deQo database, timber structures ranged from 175-296 kgCO2e/m2 (De Wolf, 2017). Given that softwood species are about 50% carbon by weight, mass timber can effectively store atmospheric carbon, which when paired with sourcing from sustainable forestry practices, can result in a reduction of atmospheric carbon. CLT can also be used in hybrid structural systems paired with either steel or concrete, reducing the carbon intensity of floor slabs, which in commercial structures contribute 47% of the structure's embodied carbon (Thornton Tomasetti, 2019). Mass timber structural systems, or hybrid structural systems employing mass timber elements are strongly encouraged to be considered for all projects types and scales to reduce the overall embodied carbon.

Wood Light Frame

A common structural system for low- and mid-rise residential and commercial project types, wood light frame uses dimensional sawn lumber and engineered lumber as the primary structural elements, for exterior load bearing walls, beams, and roof framing.

Due to the use of smaller dimensional members, there is a certain economy to these systems for both construction cost and material quantities. While this structural system has the lowest embodied carbon impacts of all structural systems, based on precedent studies it has been assigned a range of 150-258 kgCO2e/m2 (Gronvall, 2014), it is also the most limited in the range of project types and scales for which it can be employed. Wood light frame construction is often used in single-family residential, multi-family residential, and mixed use programs in projects up to six stories above grade, when paired with non-combustible stories at grade used in a "podium" configuration, (ICC, 2019) Wood is accounted for as 50% biomass as carbon stored.

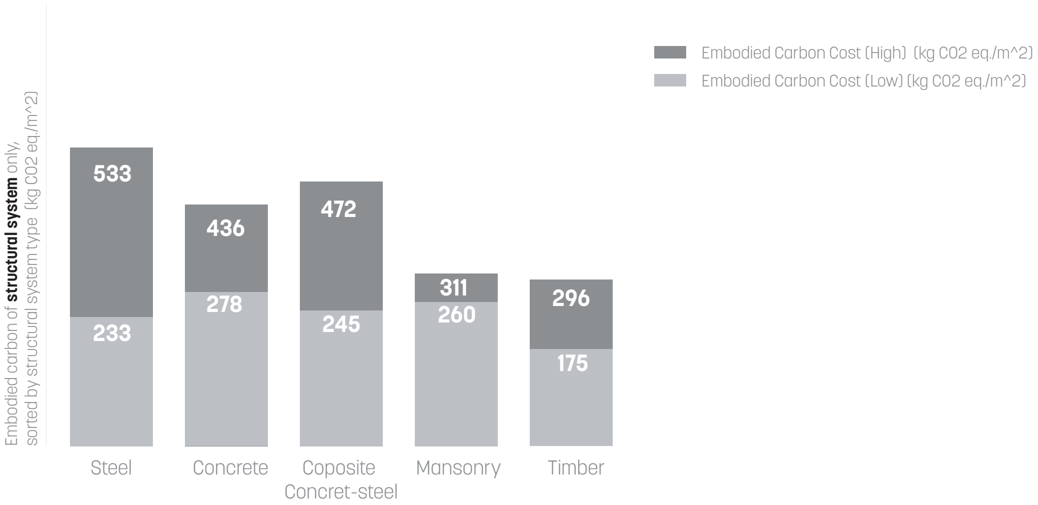


Figure 11:

Comparing carbon impacts by building structure type, per floor above ground.

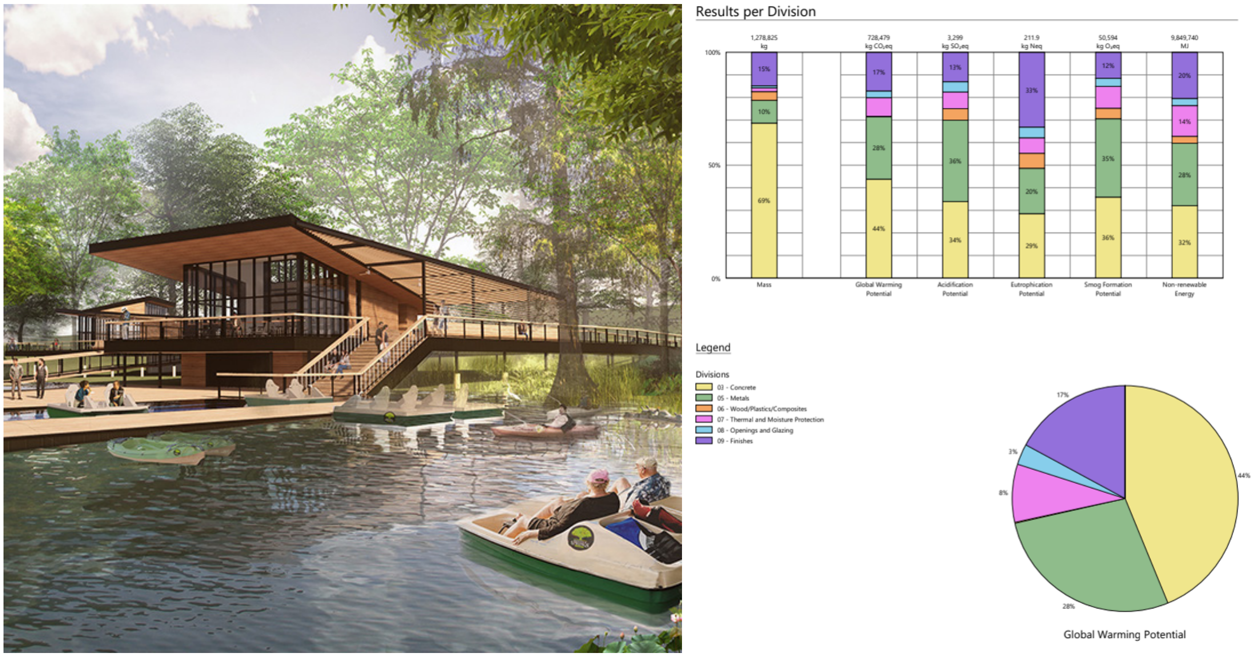


Figure 12:

Developing a complete embodied carbon assessment for the Nature Center at Bonnet Springs Park, using Tally, architecture by Sasaki, Tally by KieranTimberlake.

Building Facades

Once we have determined the building program and structural system, the next 'tier' of optional information that can help refine a building's embodied carbon is its facade material.

The Carbon Conscience calculator considers four basic types of facade systems: masonry veneer, masonry rainscreen, metal rainscreen and wood rainscreen.

The embodied carbon of each facade type was determined by Tally analysis of Sasaki's library of standard exterior wall assemblies. Each facade cladding type was analyzed using three exterior wall back-up types: cast-in-place concrete (assumed 8" thick), concrete masonry units (assumed hollow, nominal 8" thick), and cold-formed metal framing (assumed 6" deep, 16 gauge studs at 16" on-center.) Twenty-four of these assemblies were analyzed using Tally's "Full Building Assessment" method, and the results for Global Warming Potential, expressed in kgCO2e/m2 were grouped into four facade groups: masonry veneer, masonry rainscreen, metal rainscreen, and wood rainscreen.

Note: the results of our in-house calculations were corroborated by Payette's Kaleidoscope facade carbon calculator tool, released in 2020.

The contribution of the embodied carbon to the CarbonConscience calculation is based on the average of all assemblies within the facade group - each facade group is then weighted against the average of all, to derive a modifying factor. The product of this factor and the CLF average of embodied carbon per building program yields the embodied carbon value for the remaining 25% of the building's total embodied carbon (with the other 75% being sourced from the structural factor.)

Facade Groups - General Notes

All facade types that were modeled shared some common components:

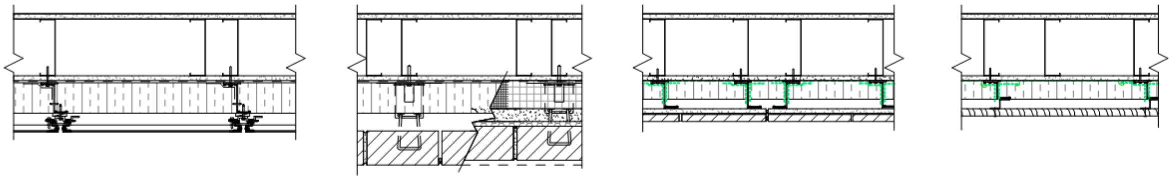
- 3" high density mineral wool continuous insulation.
- Air barrier for concrete substrates: Self-adhered sheet air barrier applied directly over cast-in-place concrete and concrete masonry unit substrates.
- Air barrier for cold-formed metal framing substrates: ⅝" fiberglass mat gypsum sheathing was modeled as the substrate.

Metal Rainscreen: this group of rainscreen panel claddings include aluminum composite material (ACM) and metal plate panel rainscreen systems and their related subframing. This average global warming potential of this category was the highest (GWP) of the four.

Masonry Veneer: this group includes masonry-type exterior claddings between 2 and 4 inches thick, composed of brick, precast concrete, and stone anchored with galvanized steel masonry ties or stone anchors. The continuous mineral wool insulation is assumed to be installed with fasteners.

Masonry Rainscreen: this group of thinner masonry panel rainscreen cladding systems less than 2” thick, and includes precast concrete and terracotta systems, and their related subframing.

Wood Rainscreen: this group of rainscreen claddings consists of domestic softwood species installed horizontally over subframing. Given the low embodied carbon of wood cladding, including its potential to sequester carbon, this category has the lowest GWP of the four.



Metal Rainscreen **Masonry Veneer** **Masonry Rainscreen** **Wood Rainscreen**

Figure 13:

Exterior wall assembly details representative of each facade group analyzed for Architecture Land Uses by Sasaki.

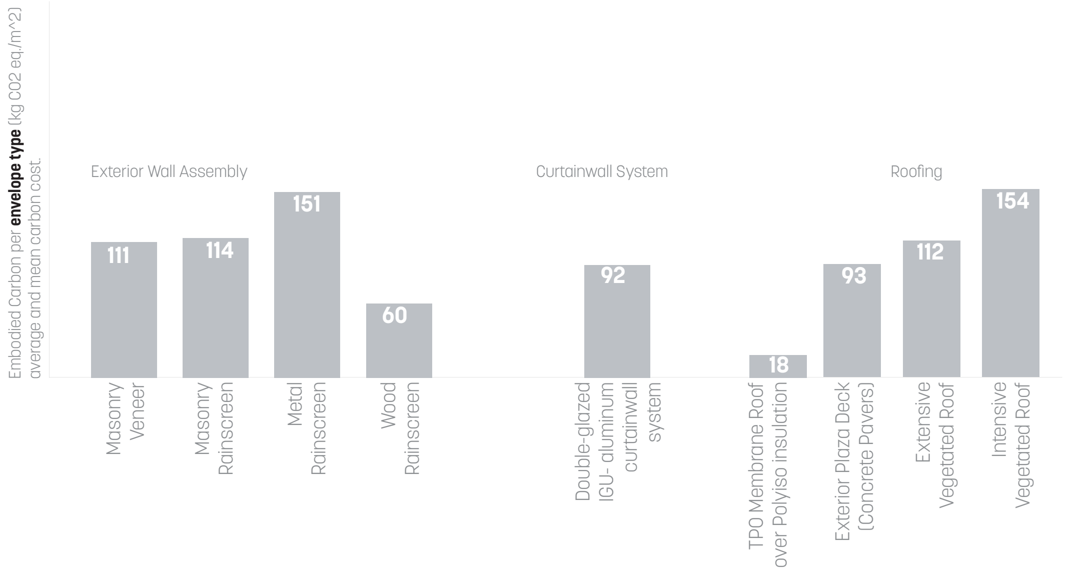


Figure 14:

Comparing carbon impacts by building envelope type.

In many areas of our research, we identified a range or metrics, methods, or results for the various carbon factors investigated. As a result, we realized the need to provide a high and low range estimate for embodied carbon per land use based on the ranges found in literature and accounting for variation in potential detailing of constructed elements. For certain elements, we extrapolated for specific assemblies based on data from similar or comparable elements found in literature. For other elements, we needed to perform a series of calculations to translate cited source data to result in estimates of kgC emissions per kg material, or kgC sequestered per square meter of land coverage. As a live tool, this data set currently reflects the literature review conducted from 2018-2020, but will be curated moving forward. As a beta tool, we are inviting critique, and will begin soliciting peer review in 2021.

Conclusions: How to design with a Carbon Conscience

In the course of our research, a few key principles emerged as consistent concepts towards designing with a Carbon Conscience, and are similar to concepts as shared in other carbon calculators (Conrad, 2020; CLF, 2017; CLF, 2020; deQ0, 2014; deQuo, 2020; EC3 website, 2020) and aggregate literature reviews or LCAs (Hammond and Jones, 2008; Mukherjee and Cass, 2011; Antti, 2013; Mohan and MacDonald, 2016; Robert, Andre and Prideaux, 2019; Bergman et. al., 2014; Athena website, 2020). These principles address the biggest potential impacts that can reduce the embodied carbon of a project early in the design process. These principles only relate to carbon, and do not prioritize or address social, cultural, aesthetic, or economic values that would also be considerations within the design process. The Carbon Conscience tool and these recommendations provide an additional metric with which to evaluate design options.

Key decisions for buildings early in the design process can have big impacts on embodied carbon.

- The embodied carbon impacts of buildings can be 2 to 10 times that of landscape per floor. When dealing with multi-floor structures, the impact is scaled to the number of stories, geometrically increasing the carbon impacts. Key decisions for buildings early in the process can have the biggest impacts for an overall project's carbon footprint, from size and program to structural and envelope considerations.
- Design compact buildings with efficient use of building materials. Use of Carbon Conscience can demonstrate that compact, mid-rise buildings are most effective at accommodating a space program with the least amount of structure, foundations, and exterior envelope. When balanced with operational energy reductions for passive solar orientation, daylighting and ventilation, this strategy can help minimize the impact of our design work on the environment.
- Wherever possible, consider the adaptive reuse of existing structures before planning for demolition or new construction. Because approximately 75% of the embodied carbon of a building is in the building structure, consider reuse of an existing building structure while updating envelope, systems and interiors. Explore future implications of these choices in terms of code compliance upgrades, phasing and scheduling, and any potential for hazardous waste mitigation.
- Consider structural materials early in the design. The Carbon Conscience tool can demonstrate the importance of minimizing the use of concrete and steel. With concrete structures, minimize the use of cement in the concrete mix. For all possible projects, consider the use of mass timber for structural systems, within the constraints of building codes, and limitations for long spans in timber. Understand the implications of structural choices on relevant factors that will impact the future design, including bay spacing, floor-to-floor heights, maximum long span challenges, and code requirements. Optimize the structural grid for material efficiency.
- Consider facade materials early in the design. Use wood and brick facades where possible, using natural materials low in embodied carbon. Minimize the use of curtain wall and spandrel glass construction, to reduce emissions from both embodied carbon and operational energy. Understand the implications of facade materials choices on relevant factors that will impact the future design, including maintenance considerations, durability and longevity. Source materials as locally as possible.

Preserve and protect existing habitats, with a priority for mature forests and wetlands.

- One of the best ways to limit emissions from site demolition is to protect existing on-site carbon stores. Forests and wetlands can have a very high amount of carbon stored – ranging from 8 kgC/m2 to over 20 kgC/m2 (Pan et. al., 2016). The best way to preserve these carbon stores is to manage existing habitats, monitoring and protecting their health during and after construction. In comparison, demolition of turf, surface pavements, and minor structures is relatively low carbon emissions, especially with large demolition equipment and short transportation distances.

Figure 15:

Surgical installation of circulation boardwalks within existing wetland habitat at Bonnet Springs Park, in Lakeland FL, landscape architecture by Sasaki.

Salvage material on site and limit construction waste transportation.

- For larger sites, on-site salvage and processing of waste hardscape materials such as concrete pavements, aggregate base, or bituminous pavements can have significant savings in transportation costs (Mukherjee and Cass, 2011) and offset imported material costs (Jiménez et. al., 2017). While this is the only salvage included within the calculator, in a detailed design project there are a wide range of creative strategies for material salvage and reuse, all of which can be leveraged for significant design impacts and low carbon costs.

Figure 16:

Xuhui Runway Park salvaged existing concrete runway for park paving, landscape architecture by Sasaki.

Minimize hardscape and maximize low-maintenance softscape land uses.

- Hardscapes always have a net carbon cost and should be used frugally, with a specific function, use, or expression that is worth the investment in money and carbon impacts. The overscaling of hardscapes compared to their intended use has become common in many design communities, from oversized civic plazas in Asia to oversized parking requirements within the United States. The return to human-scaled environments, championed by designers such as Jan Gehl, nonprofits such as the Project for Public Space, and academics such as Serge Salat and Anne Spirn, has been an interdisciplinary movement that is slowly influencing regulatory institutional reform. Advocating for a higher proportion of high quality, biodiverse greenspace within projects and reducing hardscape effectively trades a carbon negative (or net emissive) land use for a carbon positive (or net sequestering) land use.

Figure 17:

A prominent civic core, including gardens, bosques, and lawns replaces an oversized parking lot at Carnegie Mellon University Tepper Quadrangle, Landscape Architecture by Sasaki.

Minimize use of concrete and conventional cement in both architecture and hardscape sitework; explore alternative types of cements and alternative hardscape materials to concrete.

- Cement is the highest embodied carbon masonry hardscape material due to the carbon costs of its fabrication, requiring high energy inputs to produce clinker through sintering, and emitting CO2 as a chemical byproduct of its formation. Cement has been estimated to account for approximately 8% of the world's carbon emissions (Lehne and Preston, 2018). While there are numerous studies and research into low-carbon cements, the industry standards most commonly used are Type I and Type II Portland cements. The three most common substitutes found are Type IP, IS, and IL cements. Type IP cements are a portland-pozzolan cement blend that replaces a portion of the cement with pozzolanic ash and is suitable for replacement of Type II Portland cements. Similarly, Type IS and IL cements are a portland-slag cement blend, and a portland-limestone cement (Johansen et al., 2006), that are suitable for replacement of Type I Portland cements. Carbon factors for these types of cement were found to be lower, varying per specific cement composition and fabrication facility (Hammond and Jones 2008, FHWA 2011). This reduction in emissions can be substantial, and is accounted for in the Carbon Conscience calculator as the low range of estimates for hardscapes using cement, including concrete and mortar assemblies.

Substitute fabricated concrete materials with quarried materials or air-dried brick.

- The carbon factors of quarried and finished stone are lower than those of typical Portland cement concrete (Mukherjee and Cass, 2011). Crushed aggregates and mined and screened sand are also much lower than typical concrete. With approximately equal transportation costs, the replacement of concrete by stone for such assemblies as dry stack stone walls or stone pavers over compacted aggregate base with sand swept joints, can have dramatic carbon savings. Note, however, that these savings are effectively lost for stone veneer assemblies, which rely on concrete for their structure, or when stone pavers overlay a concrete sub-slab. Air-dried brick has similar savings to the use of stone, however kiln-dried brick has a carbon factor closer to typical concrete (Mohan and MacDonald, 2016).

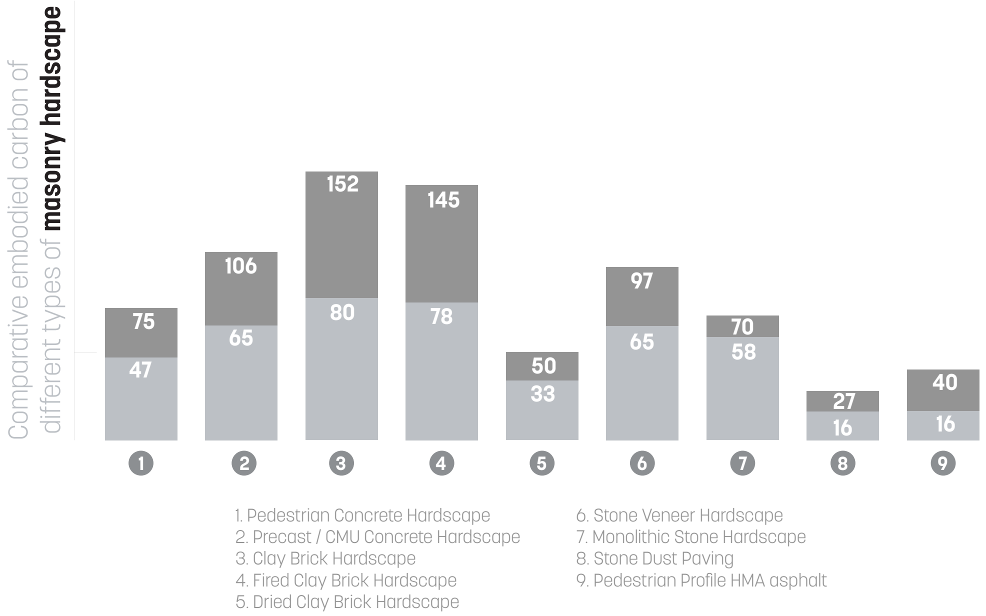


Figure 18:

Comparative embodied carbon of different types of masonry hardscape, using Carbon Conscience dataset.

Minimize the use of metals and plastics.

- Metals and plastics are both carbon-intensive families of materials. Metals require mining, smelting, and fabrication; in some cases this involves extreme amounts of energy, such as for aluminum (Mohan and MacDonald, 2016) . Within the steels, mild steel is most carbon efficient, even when accounting for a paint application, followed by galvanized steel and then stainless steel, due to the carbon costs associated with zinc versus chromium and nickel. Plastics and high density foams are often petro-chemical products that require complex fabrication and carry high carbon factors (Robert, Andre and Prideaux, 2019).

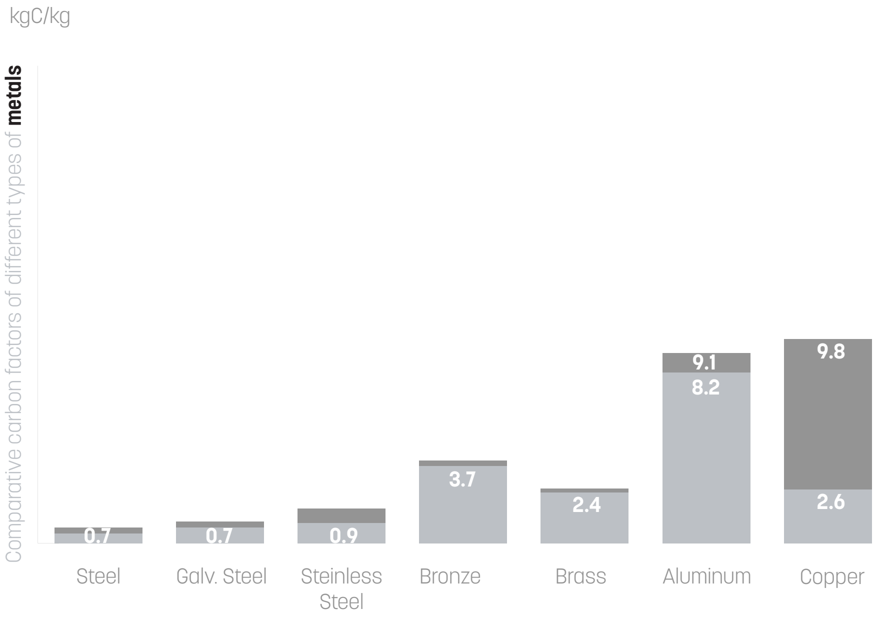


Figure 19:

Comparative carbon factors of different types of metals, using Carbon Conscience dataset.

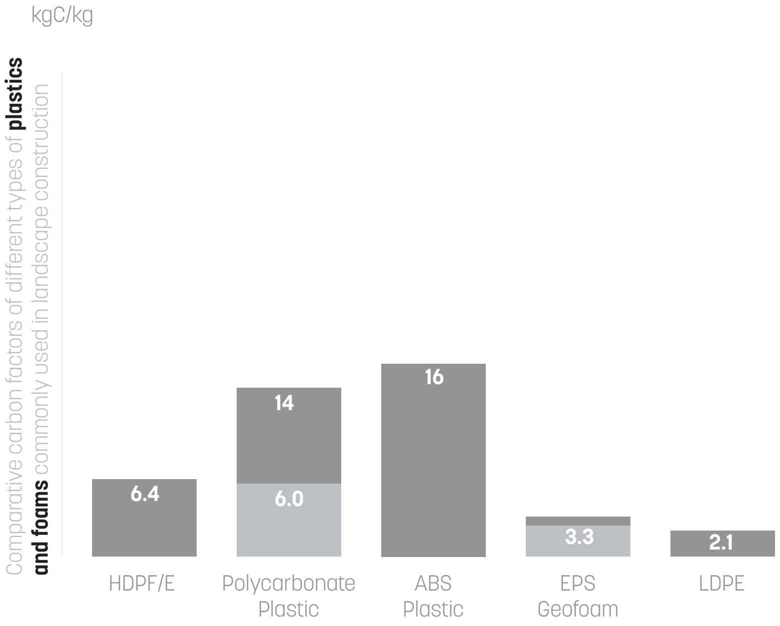


Figure 20:

Comparative carbon factors of different types of plastics and foams commonly used in landscape construction, using Carbon Conscience dataset.

Prioritize the use of wood, as a low carbon cost and high carbon storage material. When using wood or decking, prioritize domestically-sourced wood products from sustainably harvested sources.

- Mass timber framing for large scale projects and conventional wood framing for single- and multi-family residential are clearly the lowest-carbon structural materials available.
- Wood facades are the lowest-carbon cladding materials available for facades, although great care must be taken in detailing to make sure that they are durable and moisture-resistant. Clients must be prepared for any maintenance schedules necessary to refinish or repaint wood facades over time, and be informed as to

the expected lifespan of these and all systems. The selection of wood for exterior facades must be made carefully and within the context of woods available in the region of the project location.

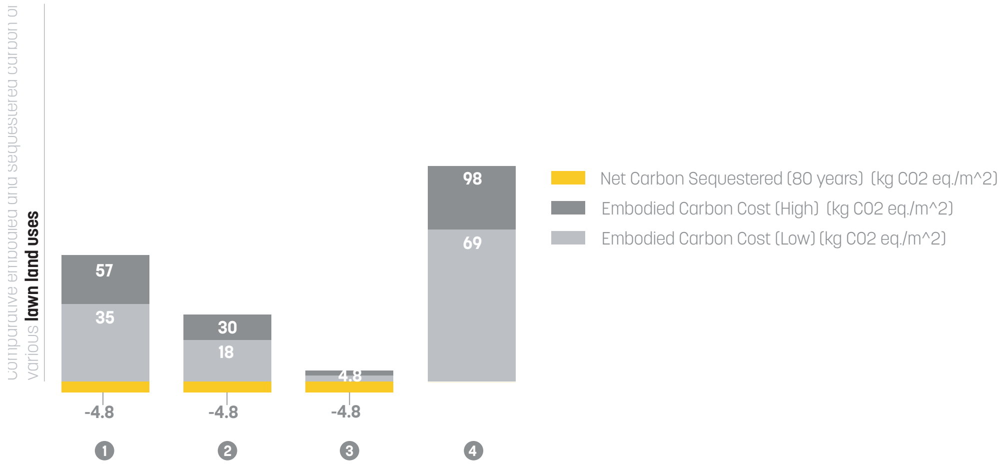
- All woods should be sourced from companies that harvest with certified sustainable practices, such as FSC (Forest Stewardship Council).
- Sustainably harvested wood products can take advantage of high carbon sequestration rates in young tree stands and store the carbon in the built environment (Bergman et al., 2014). The use of sustainably harvested wood should be encouraged as a carbon store within the built environment and detailed to last for decades. Domestically sourcing wood can halve the embodied carbon through reduction in transportation costs. While tropical hardwoods such as Ipe have become standard decking materials in the landscape, domestic alternatives such as black locust, cedar, and redwood are all equally rot and termite resistant. The desire for tropical lumber is often driven by both aesthetic and durability concerns, and is understandable when designers consider a Janka hardness rating of 3700 lbf for Ipe compared with 450 lbf for redwood or 350 lbf for cedar. In the United States and Europe, Black Locust (Robinia pseudoacacia) comes the closest in hardness rating for decking materials, with a hardness of 1,700 lbf, but can have sourcing issues (https://www.wood-database.com/).
- Relatively new wood products have addressed this need, including a range of thermally and chemically treated wood products that either use torrefaction or acetylation to effectively melt the lignin in the wood tissue to create a hard, rot-resistant matrix in the wood products (Aro, 2018). In the Carbon Conscience calculator, only thermally modified decking was added to the land use data set due to a lack of competitive products in chemically modified products.
- In addition to the reduced transportation costs associated with domestically sourced hardwood, there has been increasing reporting of illegally harvested timber products entering global trade (Brack, 2003). This increases the importance of Chain-of-Custody (CoC) certifications and stamping of timber, especially as local regulators are moving away from cargo certification, such as in Brazil and Indonesia (Spring, 2020; Jong, 2020). The authors of this article recommend international wood products be certified by third party organizations, such as Sustainable Forestry Initiative (SFI), Programme for Endorsement of Forest Certification (PEFC), or Forestry Stewardship Council (FSC). Note, company certification alone may not suffice to guarantee product origin, but rather stamped timer with a documented CoC sourced from a certified managed forest or stand. For more information on this issue, please see https://forestlegality.org.

Figure 21:

Use of wood for finish material and in structure at the Event Center, in Bonnet Springs Park, Lakeland FL, Architecture by Sasaki.

Minimize turf grasses in planting design, saving them for high use areas.

- From a carbon sequestered and stored perspective, turf grasses can sequester carbon and effectively contribute to carbon stored in soils if properly managed (Pouyat et al., 2009), (Qian et al., 2002), (McPherson & Simpson, 1999). In addition to its living biomass, turf that is mowed and mulched, or allowed to develop thatch, can increase carbon stored in non-living material and soils. However, in comparison to other softscape land uses, these contributions can be relatively low (Townsend-Small, 2010).
- From an embodied carbon perspective, turf grasses have a high range of carbon emissions based on their farming and installation (Watkins et al., 2011). Sod turfs likely result in net carbon costs or emissions, regardless of future maintenance program. If turf is sourced as sod, then the most likely methods of growing involve the use of diesel tractors for regular mowing as well as fertigation, both of which have relatively high carbon outputs (Selhorst, 2013), as well as the harvesting and transportation costs associated with including the average 1" of soil with the cut sod. In comparison, turf seed can be farmed with much lower energy inputs (Smetana and Critten, 2014), and saves on the transportation costs of the mass of the soil. Hydroseeding has variable carbon costs associated with their fertilizers, we recommend using compost tea or options with organic sources of nitrogen when specifying hydroseed installation, or generally minimizing chemical inputs as industry standards often significantly over fertilize compared with what is actually needed for optimum growth and health (Rossi, 2020; Portmess, 2009). Similarly, sprigging, a common method for installing rhizomatous turfs, can have low or high carbon costs, depending on farming methods, but saves on transportation costs over sod.
- We did not include the operations costs associated with turf lawns, as they can range from low to high carbon inputs, with high inputs for maintenance being more industry common (Portmess, 2009; Townsend-Small, 2010). In comparison with other softscape land uses, turf is a relatively low performer compared with forests, prairie, or wetlands from a carbon sequestration and storage perspective. We recommend strategically using turf only for high use spaces, such as sport fields or event lawns, and note that natural turf has a carbon benefit over synthetic turf (citation). We would recommend exchanging other areas for biodiverse plantings. For current industry recommendations, please refer to the Sports Fields Management website of Cornell University, (http://safesportsfields.cals.cornell.edu/).



1. Sod turf over ameded soil over underdrainage, with irrigation
2. Sod turf over ameded soil with irrigation
3. Hydroseed turf over ameded soil with irrigation
4. Artificial Turf Safety Surface over subdrainage

Figure 22:

Comparative embodied carbon of various 'lawn' land uses.

Maximize high carbon sequestration land uses where appropriate.

- The highest performing carbon-sequestration land uses are ecosystems that are able to lock carbon in sediments due to anaerobic conditions such as peat bogs, salt marshes, wetlands, and mangrove forests (Alongi, 2012; Asada et al., 2005; Pan et al. 2016). In these ecosystems, the annual sequestration of carbon into living biomass has the highest transfer of that carbon into long-term carbon stores once the vegetation dies and is locked in sediments, even beyond full ecosystem maturity. Depending on the region, forests can be equally effective, with a notable example being oceanic temperate rainforests, which have both high annual sequestration and significant carbon masses stored in soils (Pan et al. 2016; Easdale et al. 2019). While the Carbon Conscience calculator uses metrics taken from averages across large scale GIS research projects, not all forests are created the same. Structurally complex forests, with emergent canopy species, canopy species, and understory species, can contain higher amounts of biomass and sequester more carbon per year than similar forests in monoculture or limited diversity, and store more carbon per unit area (Gough et al., 2019). Structural complexity can be a better carbon-storage indicator than species biodiversity, as some forest types can be extremely biodiverse but have slower growth rates and less carbon stored in biomass (Buotte et al., 2020).

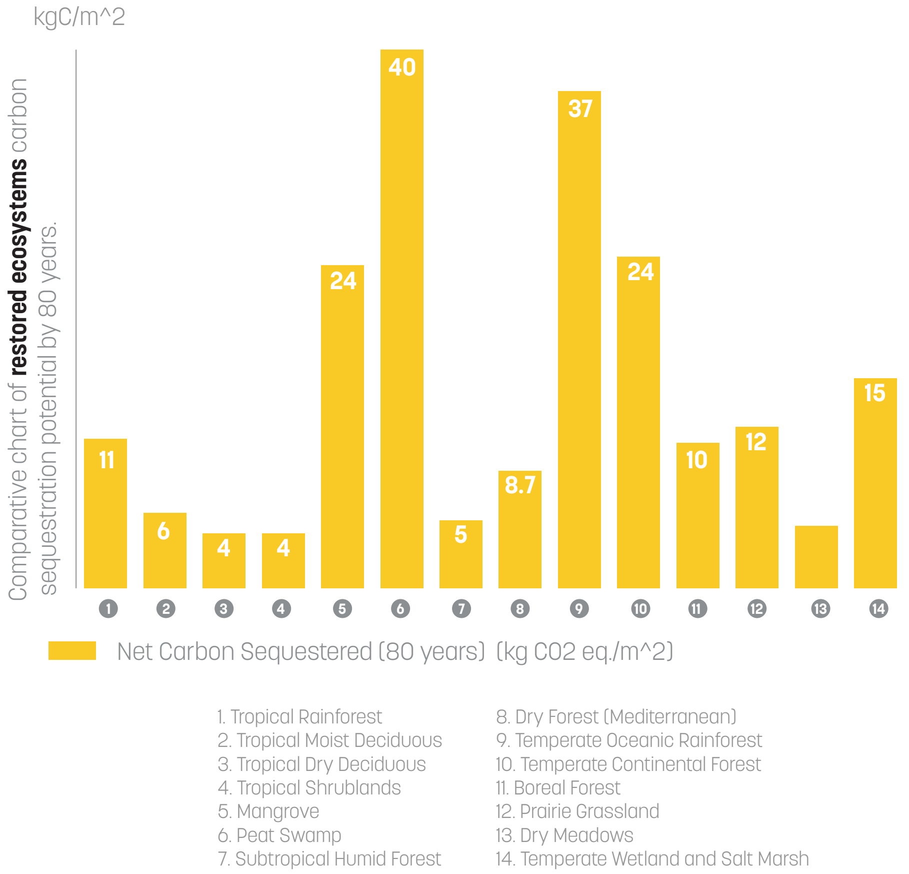


Figure 23:

Comparative chart of restored ecosystems carbon sequestration potential by 80 years.

Prioritize natural, local, and reusable materials.

- The more complex the fabrication of a material or product, the higher its associated carbon costs. Prioritizing the use of materials that can be quarried or harvested, from sand and aggregates to wood, is one of the single most effective ways to mitigating carbon impacts of construction (Reddy, 2009). Materials that require sintering such as concrete, oil inputs such as bituminous pavements, smelting such as metals, or complex chemical processes such as plastics, all have substantial embodied carbon in simply the creation of the material, even before considering fabrication, transportation, and installation.

Figure 24:

Use of regional stone and aggregates, for hardscape and gabion retaining walls, a SITES Gold landscape at Dell Medical District, University of Texas at Austin, Landscape Architecture by Sasaki.

- Transportation to a site, especially for masonry, metals, and heavy products, can be a substantial proportion of the embodied carbon of any given product or material (Gan et al. 2016). Note, in LEED V4, the regional materials credit was revised from a 500 mile radius to 100 miles - effectively a reduction of 25 times in sourcing area. While this raises the bar for this credit, we found the comparative carbon savings following this radius to be substantial. Within Carbon Conscience, we have assumed all likely regional materials, such as concrete or structural steels, are sourced within this radius in our embodied carbon estimates. Using locally-sourced materials reduces this transportation-related carbon cost.

Figure 25:

The use of regional materials, such as the example of locally manufactured brick for use at Boston City Hall, can dramatically cut down on embodied carbon associated with transportation, landscape architecture by Sasaki.

- Installation is only one part of a project, material, or product's life cycle. Where possible, using salvaged materials, reusing materials already on site, or 'upcycling' materials can effectively remove the embodied carbon for that material from the calculation of a given project (McDonough, 2002). This principle can apply to big moves, such as adaptive reuse of buildings, down to resetting cobble pavers. One way to enable this for future projects is to select durable, natural materials and consider the full life cycle of assemblies (Simonen, 2014).

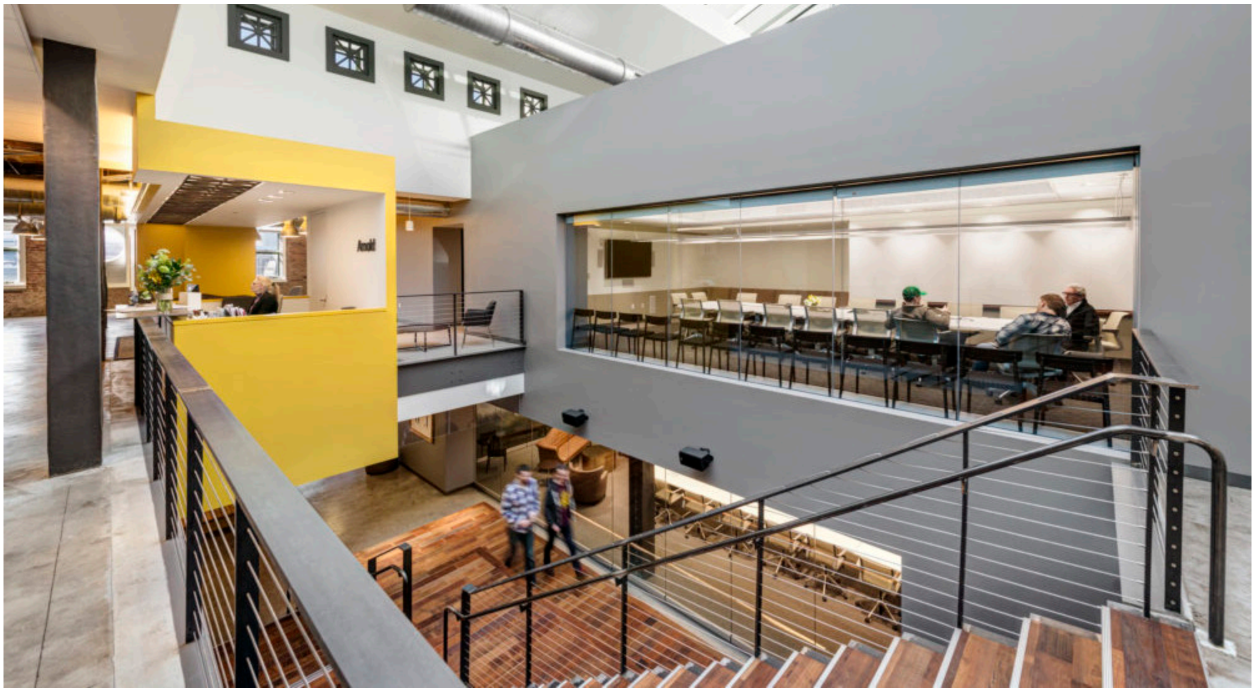


Figure 25:

An example of new strategically introducing new materials within adaptive reuse, and maximizing use of salvaged materials, including old railings as marker trays, radiator grilles as light fixtures, and reclaimed wood for stair treads, at Havas/Arnold Worldwide Headquarters, Boston, MA, Interior Architecture by Sasaki.

Less is more.

- Designing with a Carbon Conscience reconsiders the evaluation of a proposed design or plan from the perspective of the relative impact on our climate, as an additional factor to consider in addition to use, economics, and aesthetics. It reveals the comparative impacts of embodied carbon for various land uses and enables iterative design informed by carbon impacts. It shows that doing less, from a building or hardscape perspective, is always going to result in lower embodied carbon for construction. It also reveals that carbon negative softscapes require significant amounts of area to offset emissions from buildings or hardscape. We do not intend for this application to be a stand-alone factor in the evaluation of a design. Within this tool, an infill development in a densely-populated, community served by transit, would have a high embodied carbon per area score compared to a greenfield development of similar size but with a large existing-to-remain woodlands or softscape design. Carbon Conscience is best used to evaluate options within a given project - to make design teams and clients aware of what decisions they can make to reduce the anticipated emissions from the construction of their projects.

Further Investigation

Beyond the accuracy of this tool, our research also revealed a strong need for investment in academic research in all factors of our understanding of carbon in the built environment. While some aspects, such as carbon emissions associated with concrete, are exhaustively researched, others, such as embodied carbon associated with recycling processes, appear to have a less robust representation in literature. Similarly, while extensive studies have been conducted on carbon sequestered in living tissue of specific tree species or through different agricultural approaches, carbon sequestration for gardens and urban landscapes has been studied by a relatively small group of experts, primarily from the United States or Europe. Specific areas of potential investment in investigation that appear to be needed to further inform LCAs and tools such as Carbon Conscience include regional influences on carbon factors, energy source alternatives in material fabrication, carbon sequestration in horticultural land uses, and carbon assessments of the nursery industry.

The best way to enhance tools such as Carbon Conscience, Tally, or Pathfinder, are for academic research partners to work with design professional teams, to test projects and field verify or challenge results and predictions. Recent studies and advances, such as the Carbon Leadership Form's 2017 "Embodied Carbon Benchmark Study" and MIT's Database of Embodied Quantity Outputs "deQo," and research at MIT's Concrete Sustainability Hub shows exciting advancements in this direction.

Data Tables

Use the following link to view and review the database for Carbon Conscience.

https://docs.google.com/spreadsheets/d/1k65nUnU86N2Bx8m7FfqO_gFBeeS9H_gxl69xh8bdX-Y/edit?usp=sharing

Tables inlcuded:

Table 1: Landscape Land Use Carbon Data Set

Table 2: Architecture Land Use Carbon Data Set

Table 3: Landscape Materials and Assemblies Data Set

Table 4: Landscape Materials Carbon Costs Data Set

Table 5: Landscape Carbon Sequestration Data Set

Appendix A:

A quick guide to designing with a Carbon Conscience - a graphic summary:

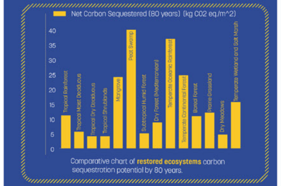
How to Design with a

Carbon Conscience

Designers' toolkit for DO's and DON'Ts

Pre-Design

Maximize high carbon sequestration land uses where appropriate: **peat bogs, salt marshes, wetlands, and mangrove forests.**



Comparative chart of **restored ecosystems** carbon sequestration potential by 80 years.

Prioritize Salvage material on site and limit construction waste transportation. **Reuse materials**, from adaptive reuse of buildings to resetting cobble pavers

Minimize demolition of existing mature or healthy habitats.

Minimize removal of large established trees.

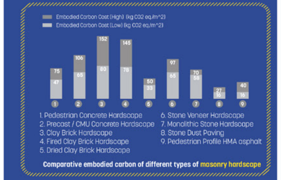
Reduce or limit off-hauling of waste or demolition debris.

Material Selection

Explore alternative types of cements and alternative hardscape materials to concrete.

Substitute fabricated concrete materials with **quarried materials, air-dried brick, crushed aggregates and mined and screened sand.**

Note: kiln-dried brick has a carbon factor closer to typical concrete



Comparative embodied carbon of different types of masonry hardscape

Prioritize the use of **wood**, as a low carbon cost and high carbon storage material.

Prioritize domestically-sourced wood products from sustainably harvested sources.

Prioritize **natural, local, and reusable** materials.

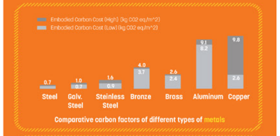
Using **locally-sourced** materials reduces transportation-related carbon cost.

Reduce use of **concrete and conventional cement** in both architecture and hardscape sitework.

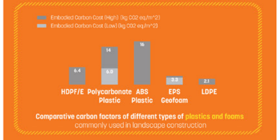
Cement is the highest embodied carbon masonry hardscape material

Minimize the use of **metals** and **plastics**.

Metals and plastics are both carbon-intensive families of materials.



Comparative carbon factors of different types of metals



Comparative carbon factors of different types of plastics and foams commonly used in landscape construction

Minimize the use of **material** that is **over 100mi** for transportation

Minimize **hardscape** and **maximize low-maintenance softscape** land uses.

Advocating for a higher proportion of high quality **greenspace** while reducing hardscape effectively trades a carbon negative (or net emissive) land use for a carbon positive (or net sequestering) land use.

maximize **structurally complex green spaces**, such as woodlands with overstory canopy and understory vegetation, or biodiverse prairie grasslands, where appropriate.

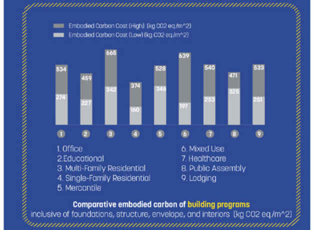
Prioritiaze the use of **mass timber**.

Consider the adaptive **reuse of existing structures**.

Optimize the **structural grid** for material efficiency

Consider a component or system's specific longevity relative to its estimated embodied carbon.

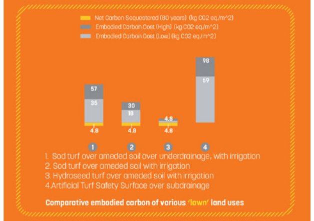
Detail for durability and longevity.



Comparative embodied carbon of building programs inclusive of foundations, structure, envelope, and interiors (kg C02 eq./m^2)

Don't design **oversized plazas, parking** lots.

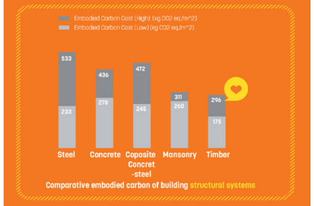
Minimize the use of **turf grasses** if not necessary or can have other softscape types.



Comparative embodied carbon of various 'lawn' land uses

Minimize the use of **steel.**

Minimize the use of **curtain wall** and **spandrel glass construction.**



Comparative embodied carbon of building structural systems

Comparative embodied carbon of building envelope types, using average and mean carbon cost (kg C02 eq./m^2)

Less is more.

Designing with a Carbon Conscience reconsiders the evaluation of a proposed design or plan from the perspective of the relavant impact on our climate, as an additional factor to consider to use, economics, and aesthetics. It reveals the comparative impacts of embodied carbon for various land uses and enables iterative design informed by carbon impacts.

It shows that doing less, from a building or hardscape perspective, is always going to result in lower embodied carbon for construction. It also reveals that carbon negative softscapes require significant amounts of area to offset emissions from buildings or hardscape.

We do not intend for this application to be a stand-alone factor in the evaluation of a design. Carbon Conscience is best used to evaluate options within a given project - to make design teams and clients aware of what decisions they can make to reduce the anticipated emissions from the construction of their projects.

Appendix B:

Additional Carbon Calculators and LCAs Reviews and Resource Recommendations

Tally & EC3

https://kierantimberlake.com/page/tally

- Tally is a Revit plugin developed by KieranTimberlake that reads material definitions and volumes from the Revit model to rapidly produce whole-building Life Cycle Assessments. KieranTimberlake is an architecture firm with an in-house research department who designs custom tools.
- Tally users analyze each Revit material in the model, and assign it a corresponding Tally material definition which has been sourced from material EPDs found on the Carbon Leadership Forum's (CLF) EC3 tool. CLF is a non-profit organization bringing together professionals and academics to address embodied carbon in the built environment.
- Revit models in any stage of development can be analyzed. Running Tally on Schematic Design level Revit models can provide critical early guidance to designers, and can provide a baseline model for use in tracking the progress of the embodied carbon targets as the model develops. These early models can also serve as the required baseline in pursuit of the LEED NC-v4 MRc2 credit.
- Tally can also compare Revit design options to further help designers at key decision points in the design process. As the model becomes more developed, the better the material take-offs and material assumptions can be, yielding more accurate results.
- Because of the significance of embodied carbon contributed by a building's structural systems, it is critical that structural Linked Models are analyzed in Tally as well, and it is highly recommended that designers bring their structural engineers into the process early on, to establish embodied carbon project goals and set standards for either the engineer's use of Tally, or allowing access to their models so Tally can include their embodied carbon contribution.
- At the time of this paper, Tally costs approximately $1200 per floating license per year.
- Because of the seamless integration into Revit, Tally is our top recommendation for detailed embodied carbon and overall LCA studies for buildings once in schematic design phases.

Pathfinder

https://climatepositivedesign.com/

- Pathfinder is a web-based application to evaluate the carbon impacts of landscape architecture. Pathfinder is hosted through the Carbon Positive Design website, a joint effort of the design firms CMG Landscape Architecture and Atelier 10. It is the first detailed carbon calculator for built landscapes, surpassing former calculators such as Low Carbon Living, Build Carbon Neutral, and tools from Architecture 2030 in terms of breadth and specificity to landscape.
- Pathfinder works through a web-based questionnaire for quantities of materials included within a project, and projects full life emissions and carbon sequestration. Methods and citations are provided, the majority of which is taken from Athena LCAs and key white papers.
- In addition to the carbon calculator tool, the climate positive design website has aggregate useful links, concept explanations, and case studies from CMG's portfolio.
- At the time of this paper, Pathfinder is free.
- We recommend pathfinder as the best tool for detailed landscape design analysis when full materials take-offs are available for a project.

Athena Sustainable Materials Institute

http://www.athenasmi.org/

- Athena Sustainable Materials Institute (ASMI) is a Canadian non-profit think tank organized around life-cycle-assessment of products and whole buildings, including the creation and curation of LCA design tools and an impact estimator for buildings and pavement. In addition to these aggregate LCA tools, ASMI is involved across the LCA industry from development of ANSI standards to peer review of EPDs, and performs contracted LCA research for manufacturers and suppliers. ASMI tools are targeted to North American projects, and are subscription based.

- The Athena EcoCalculator tools are relatively fast tools to use through provided spreadsheets to quickly assess potential impacts at a building specific - assembly concept design level of detail.
- The Athena Impact Estimator for Buildings is a stand alone software that involves modeling a building within the program.
- At the time of this paper, the Athena tools are free.
- Athena's tools are linked to a proprietary database and from the US life Cycle Inventory Database. The quality and comprehensiveness of the data included makes this product one of our top recommendations for detailed design of buildings at concept phases and evaluation of specific assemblies

Other Resources

These resources were all found to be helpful, with clear logic and cited sources of information.

Additional Embodied Carbon Calculators

- One-Click LCA: The engineer's software of choice for LCAs as well as embodied carbon calculations. https://www.oneclicklca.com/
- Beacon (for structural systems), from the Embodied Carbon Lab at Thornton Tomasetti : https://core-studio.gitbook.io/beacon/
- Kaleidoscope (for facades) from Payette: https://www.payette.com/kaleidoscope/
- Concrete LCA tool (for concrete mixes) from ZGF: https://www.zgf.com/news_post/lca-calculator-reduces-concretes-embodied-carbon/
- EA Tool (for structural systems) from SOM: https://www.som.com/news/new_tool_measures_emissions_from_buildings

Additional LCA resources

- Epic (LCA) Database, University of Melbourne. https://msd.unimelb.edu.au/research/projects/current/environmental-performance-in-construction/epic-database
- U.S. Life Cycle Inventory Database. https://www.nrel.gov/lci/
- EPD International. https://www.environdec.com/

Energy Modeling Programs

- Cove.tool (energy modeling for individual builds and neighborhoods): https://www.cove.tools/
- IES VE (whole building energy simulation): https://www.iesve.com/software/building-energy-modeling
- DesignBuilder (performance analysis tools): https://designbuilder.co.uk/

Additional Resources:

- Carbon Smart Materials Pallette: https://materialspalette.org/
- EPD Quicksheet: https://architecture2030.org/epd-quicksheet/
- Architecture 2030: https://architecture2030.org/
- USGBC - How LEED V4.1 addresses embodied carbon: https://www.usgbc.org/articles/how-leed-v41-addresses-embodied-carbon
- Climate Positive Design - Resource Recommendations: https://climatepositivedesign.com/resources/
- Society for Ecological Restoration Resource Center: https://www.ser-rrc.org/
- iTree (for detailed arboriculture tools): https://www.itreetools.org/
- Eco GIS (monitor energy consumption and CO2 emissions): http://www.ecogis.info/

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