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Using Green Infrastructure to Create Carbon Neutral Cities: An Accounting Methodology

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Many cities across the world have the aspiration to be carbon neutral. However, this requires energy efficient buildings and the implementation of green infrastructure. A major challenge in this regard is that carbon dioxide emissions may be regarded as being embodied within our construction materials. Embodied energy is the quantity of energy required to process and supply these materials to an urban development and embodied carbon can be measured as the total weight of carbon dioxide used in the extraction, manufacture and delivery of the materials. Determining the amount of carbon dioxide capture required to offset the embodied carbon in urban developments is a complex task. This paper describes the findings of an Australian Research Council funded project that has examined the use of street trees to create carbon neutral developments in Australia. An accounting methodology is presented that calculates the embodied carbon over the material supply chain using a cradle to gate approach. This methodology is applied to a typical residential development where a permeable paving system is used for stormwater control. It was found that the embodied carbon in a 370 mm deep permeable pavement system is approximately 5.9 t / 100 m^2 of pavement. Trees typically take 6 to 10 y to transform from their juvenile planting state to full maturity and they uptake different quantities of carbon dioxide throughout this transformation. This leads to an initial carbon deficit, but this is readily restored over the typical 50-year life of a tree, during which time there is a quantifiable net-positive contribution to carbon capture. It was found that four street trees planted per 100 m^2 of permeable paving is sufficient to create carbon neutral permeable pavement systems. This paper demonstrates that street trees can be used in combination with permeable pavements to create carbon neutral developments. This is relatively new concept and the contribution of this paper is to demonstrate how to control the potentially problematic issue of tree roots damaging pavements.

1. Introduction

1.1 Permeable pavements

A permeable pavement system is a Water Sensitive Urban Design (WSUD) technology that is designed to infiltrate stormwater runoff into underlying soils. WSUD is synonymous with low impact development (LID) and sustainable urban drainage systems (SUDS). According to Myers et al. (2013) and Wong and Brown (2009), the main objectives of WSUD are to:

- reduce potable water demand by adopting water efficient tools and harvesting stormwater;
- treat wastewater to allow its reuse for suitable purpose and to minimise wastewater discharge into receiving waters;
- treatment of urban runoff to meet water quality objectives, to allow its reuse, to support biodiversity conservation in receiving waters, to recharge soil moisture in the root zones of urban vegetation, and to increase groundwater infiltration;
- preservation of the natural water cycle in urban environments to support green spaces.

During the infiltration process, permeable pavements also mechanically filter sediment from stormwater (Hill and Beecham, 2018) and promote other treatment processes such as microbial digestion of organic material (Chowdhury et al., 2016), adsorption of heavy metals (Aryal et al., 2015) and volatilisation of hydrocarbons (Razzaghmanesh and Beecham, 2018).

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In addition to this intended functionality, permeable pavements allow the soil moisture below to effectively breathe by permitting evaporation of soil moisture through the pavement, therefore reducing any condensation that may form on the underside of impermeable pavement surface such as asphalt.

Permeable pavement systems consist of concrete pavers laid on top of a fine gravel bedding layer that in turn sits on a coarser gravel sub-base (or basecourse) layer. The gaps between the pavers are typically filled with the same gravel as used in the bedding layer. This facilitates stormwater infiltration into the sub-base layers and ultimately into the underlying native soil (Figure 1).

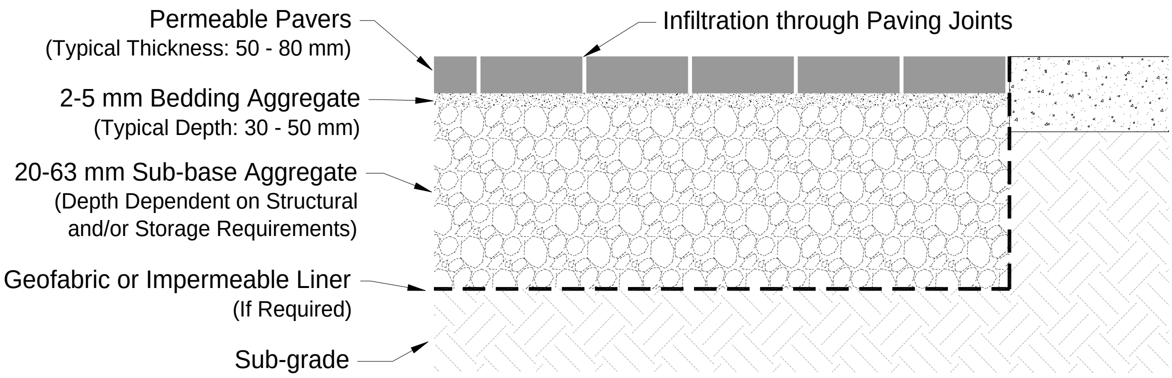

Figure 1: The four layers of a permeable pavement system (adapted from Lucke and Beecham, 2019)

Extensive research has been conducted into permeable pavements as a water sensitive urban design tool. Early permeable pavement studies focused on their use as a source control measure in terms of reducing runoff and treating and reducing stormwater pollutants (Pratt et al., 1996). More recently, Razzaghmanesh and Beecham (2018) conducted a literature review of permeable pavement studies and concluded that their field performance decreases with time due to gradual clogging, predominantly by fine sediments.

1.2 Embodied carbon

The term embodied energy has been used for over forty years to describe aggregated energy inputs to a process or system over its entire lifecycle (van Gool, 1980). Indeed, reducing embodied carbon has been one of the main concerns within the construction industry over recent years (Gardezi et al., 2015). Hammond and Jones (2008a) described how embodied carbon therefore represents the entire lifecycle concept used in lifecycle cost analyses. Sununta et al. (2017) outlined various ways in which measures such as rooftop solar photovoltaics and composting of organic waste could reduce the carbon footprint at the city scale in Thailand. At the precinct scale, Gardezi et al. (2015) showed how using recycled material in construction could reduce the embodied carbon footprint of a housing development in Malaysia by up to 18 %. However, there have been very few studies that have looked at using green infrastructure to offset the embodied carbon of urban developments.

Cook and Knapton (2009) demonstrated that permeable pavements contain approximately half the embodied carbon of equally sized impermeable pavements that are drained conventionally. This was mainly due to the elimination of the conventional drainage system. Even so, many new developments are striving for carbon neutrality, which raises the question of how this embodied carbon could be offset. One technique is to plant street trees in recognition that they sequester carbon dioxide directly from the atmosphere at rates of between 10 kg and 30 kg per year depending on the size of the tree. This rate was derived from Stephenson et al. (2014) who undertook an analysis of 403 temperate and tropical tree species from Africa, Asia, Australasia, Central and South America, Europe and North America. There was no evidence presented in this study to suggest that climatic conditions influenced the tree mass growth rate. The main finding of this study was that that for most species mass growth rate increases continuously with tree size.

Figure 2 shows a typical arrangement of newly planted juvenile street trees planted in a permeable pavement system. While previous studies have described the potential for green infrastructure to offset embodied carbon in engineered systems, this is the first study to both quantify the potential for street trees to offset the embodied carbon in a permeable pavement system and to describe how this can be done without risking structural damage to the pavement system through uncontrolled tree root growth. The objective of this study is to investigate how permeable pavements can be made more sustainable by offsetting their embodied carbon. The contribution and novelty of this work include:

1. Developing an energy accounting method to estimate the embodied carbon in permeable pavement systems.
2. Demonstrating how urban street trees can be used to offset the embodied carbon contained in permeable pavement systems.
3. Exploring how permeable pavement systems can be developed to minimise damage by encouraging tree roots to grow deeper into the pavement structure.

Figure 2: Juvenile street trees soon after planting in a permeable pavement system in Australia

2. Accounting methodology

To estimate the number of trees needed to offset a given permeable pavement system, an accounting methodology has been developed that calculates the energy inputs over the material supply chain using a cradle to gate approach. This methodology is applied to a typical residential development where a permeable pavement system is used to control stormwater.

Table 1 shows the embodied carbon contained in the typical layers of a permeable pavement system, calculated using the University of Bath's Inventory of Carbon and Energy (Hammond and Jones, 2008b). A 370 mm deep pavement was selected for this example calculation because this is a very typical depth profile for Australian permeable pavements. For example, 80 mm thick pavers are almost universally used in Australia for permeable paving systems that are subject to regular vehicular traffic. Similarly, the bedding layer is mostly in the range of 30 to 50 mm in depth (Lucke and Beecham, 2011), hence 40 mm was selected. Basecourse layers are the most variable in depth, but 250 mm is quite typical.

Table 1: Embodied carbon in typical layers of a permeable pavement system (adapted from Hammond and Jones, 2008b)

Permeable Pavement Component Layers	Embodied Carbon (kg/m^2)
80 mm thick concrete pavers	41.8
40 mm bedding layer of 3 to 6 mm gravel	2.4
250 mm layer of 20 mm basecourse gravel	15.0

Street trees can be planted to offset the amount of embodied carbon shown in Table 1. As shown in Figure 2, it is juvenile forms of street trees that are usually planted in permeable pavement systems. These juveniles typically take around 10 y to reach full maturity, with the lifespan of the tree being approximately 50 y (Lucke and Beecham, 2019). To illustrate this point, the same trees that were shown as juvenile plantings in Figure 2 are shown as 7-year-old near-mature trees in Figure 4.

According to Cook and Knapton (2009), the mass of a tree is directly proportional to its diameter and height and an additional 20 % mass is contained in the root system. The same authors stated that the carbon content of a tree is approximately 50 % by mass and the sequestration rates vary between 10 and 30 kg per year depending on the age of the tree. In this analysis, it was assumed that the tree height and diameter increase linearly from planting to year 10, and that these measurements remain constant thereafter.

A flowchart showing the accounting methodology is presented in Figure 3.

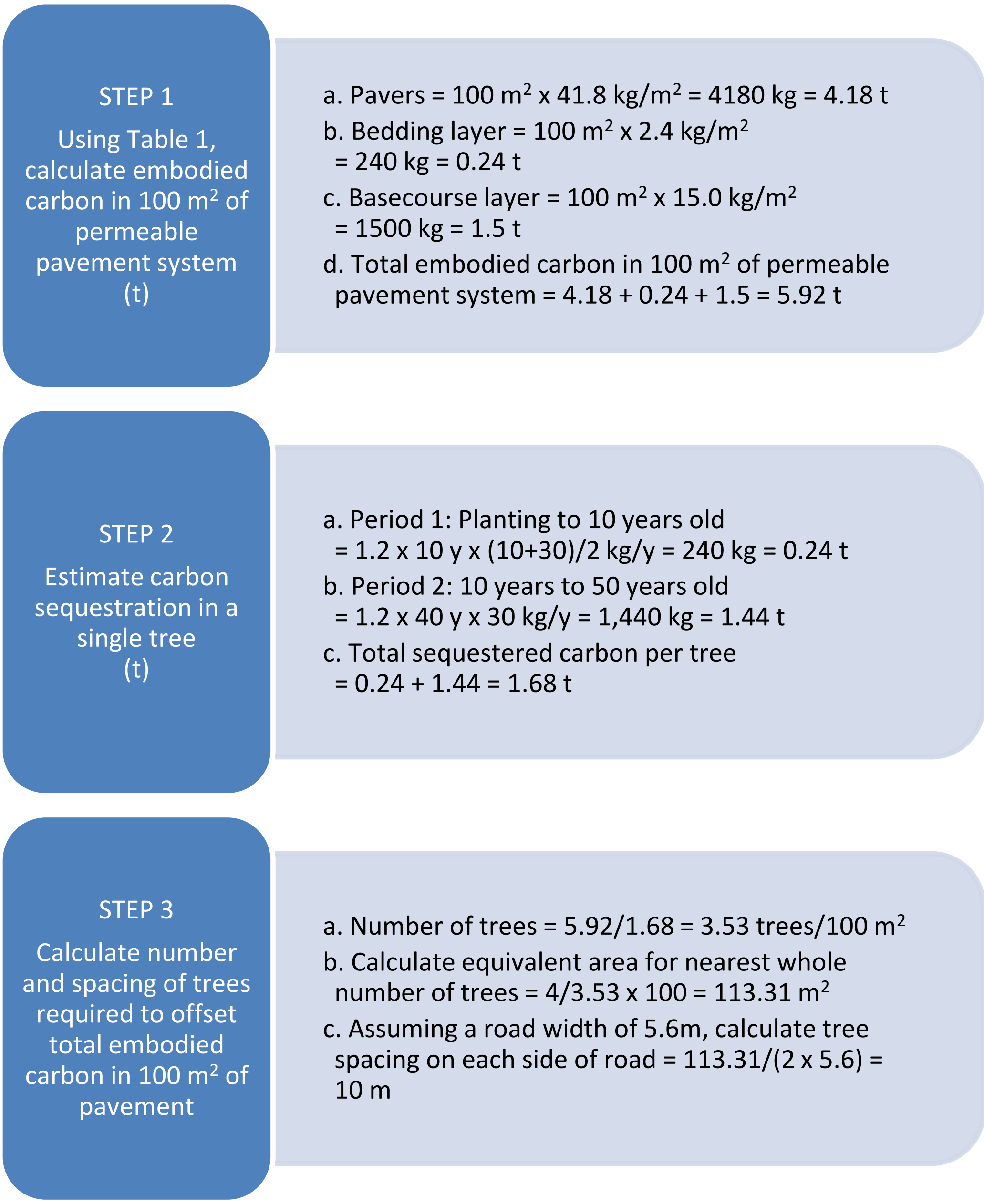

Figure 3: Flowchart of accounting methodology

3. Results and discussion

3.1 Embodied carbon in a permeable pavement

From Table 1 and Figure 3, the embodied carbon in a 370 mm deep permeable pavement system can be calculated as 5.9 t/ 100 m^2 of pavement. This is calculated in kilograms as 100 m^2 x (41.8 + 2.4 + 15.0) kg/m^2, which is then converted to t.

From Figure 3, a single street tree sequesters 1.68 t of carbon dioxide over 50 y. Equating this sequestering rate to the values in Table 1 results in a requirement for approximately four trees to be planted every 100 m^2 of permeable paving to fully offset the embodied carbon contained in the pavement. Applying this planting rate to a typical road situation would result in a tree being planted every 10 m on both sides off the road if it was paved with permeable paving (calculation details are presented in Figure 3).

3.2 Street trees integrated into permeable pavement systems

Planting a street tree every 10 m along a roadway is quite achievable, as shown in Figure 4, but the coexistence of street trees and pavements can lead to structural problems due to shallow root growth causing damage to roads, paths and underground services. Lucke and Beecham (2019) investigated whether pavement damage by roots could be reduced by planting trees in a permeable pavement system with an underlying gravel basecourse layer. They conducted a six-year field experiment to measure tree growth and particularly root growth in both conventional impermeable and permeable pavements. They found that street tree roots could be encouraged to grow deeper into the underlying native soil, thereby reducing or even eliminating damage to pavements. This redirection of root growth became more noticeable in deeper compared to shallower basecourse layers.

Figure 4: Seven-year-old street trees planted in a permeable pavement system in Australia

4. Conclusion

Carbon neutrality is a worthy ambition but in the highly urbanised environments of modern society it is a difficult goal to achieve. Street trees offer one of the most cost-effective options to sequester carbon dioxide and therefore to offset the high quantities of embodied carbon that are embedded in our modern metropolitan infrastructure.

An objective method of accounting for embodied carbon has been presented in this paper and this has been extended to the estimation of the temporal distribution of carbon dioxide sequestered over the typical life of a street tree. It has been found that four street trees per 100 m^2 of permeable paving is sufficient to create carbon neutral permeable pavement systems. On a typical road system, this would require planting a street tree every 10 m on either side of the road, which is a readily achievable outcome in most urban developments.

In terms of future directions for this research, it is recommended that the accounting method described in this paper is examined for applications under different climatic conditions. This could also include how carbon sequestration varies with the age and species of trees, with different growth conditions in the environment, and potentially with the density of surrounding trees. Further research is also required to investigate the cost implications of this approach of combining street trees with permeable pavement systems.

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References

Aryal, R., Beecham, S., Lee, B., 2015, Evaluation of particle transport in permeable pavements under oil loadings, KSCE Journal of Civil Engineering, 19(7), 2000-2004.

Chowdhury, R. K., Sharvelle, S. E., Beecham, S., 2016, Greywater quality changes in a permeable pavement reservoir. Proceedings of the Institution of Civil Engineers, Water Management, 169(4), 190-198.

Cook, I., Knapton, J., 2009, Assessment of embodied carbon in conventional and permeable pavements surfaced with pavers, 9th International Conference on Concrete Block Paving, Buenos Aires, Argentina, 1-8.

Gardezi S., Shafiq N., Abdullah N., Khamidi M., Farhan S., 2015, Minimization of embodied carbon footprint from housing sector of Malaysia, Chemical Engineering Transactions, 45, 1927-1932.

Hammond, G. P., Jones, C. I., 2008a, Embodied energy and carbon in construction materials, Energy, 161(2), 87-98.

Hammond, G. P., Jones, C. I., 2008b, Inventory of carbon and energy, Beta Version V1.6a, Department of Mechanical Engineering, University of Bath, <organicexplorer.co.nz/site/organicexplore/files/ICE%20Version%201.6a.pdf> accessed 27.5.2019.

Hill, K. D., Beecham, S., 2018, The effect of particle size on sediment accumulation in permeable pavements, Water, 10(4), 1-9.

Lucke, T., Beecham, S., 2019, An infiltration approach to reducing pavement damage by street trees, Science of the Total Environment, 671, 94-100.

Lucke, T., Beecham, S., 2011, Field investigation of clogging in a permeable pavement system, Building Research and Information, 39(6), 603-615.

McPherson, E.G., 2007, Benefits based tree valuation, Arboriculture and Urban Forestry, 33(1), 1-11.

Myers, B., Chacko, P., Tjandraatmadja, G., Cook, S., Umapathi, S., Pezzinaiti, D., Sharma, A.K., 2013, The status of water sensitive urban design in South Australia. South Australia, <http://www.goyderinstitute.org/_r100/media/system/attrib/file/91/WSUD_Task%201_Report_WSUD%20Inventory_final%20for%20web.pdf> accessed 28.8.2019.

Razzaghmanesh, M., Beecham, S., 2018, A review of permeable pavement clogging investigations and recommended maintenance regimes, Water, 10(3), 1-9.

Sapdhare, H., Myers, B., Beecham, S., Brien, C., 2018, Performance of a kerb side inlet to irrigate street trees and to improve road runoff water quality: a comparison of four media types, Environmental Science and Pollution Research, 1-13.

Stephenson, N.L., A.J. Das, R. Condit, S.E. Russo, P.J. Baker, N.G. Beckman, D.A. Coomes, E.R. Lines, W.K. Morris, N. Rüger, E. Álvarez, C. Blundo, S. Bunyavejchewin, G. Chuyong, S.J. Davies, Á. Duque, C.N. Ewango, O. Flores, J.F. Franklin, H.R. Grau, Z. Hao, M.E. Harmon, S.P. Hubbell, D. Kenfack, Y. Lin, J.-R. Makana, A. Malizia, L.R. Malizia, R.J. Pabst, N. Pongpattananurak, S.-H. Su, I-F. Sun, S. Tan, D. Thomas, P.J. van Mantgem, X. Wang, S.K. Wiser, M.A. Zavala, 2014, Rate of tree carbon accumulation increases continuously with tree size, Nature, 507, 90–93.

Sununta, N., Kongboon, R., Jareansuk, L., Sampattagul, S., City Carbon Footprint Evaluation and Forecasting Case Study: Dan Sai Municipality, Loei Province of Thailand, Proceedings of the 3rd International Conference of Low Carbon Asia and Beyond (ICLCA 2017), 1-3 November 2017, Bangkok, Thailand.

Van Gool, W., 1980, Thermodynamic aspects of energy conversion, Energy, 5(8), 783–792.

Wong, T.H.F., Brown, R.R., 2009, The water sensitive city: principles for practice, Water Science and Technology, 60, 673-682.

Zhang, B., Xie, G., Zhang, C., Zhang, J., 2012, The economic benefits of rainwater-runoff reduction by urban green spaces: A case study in Beijing, China, Journal of Environmental Management, 100, 65-71.