Exploring Alternative Methods of Environmental Analysis

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ABSTRACT: While the majority of businesses focus on economic repercussions of business decisions, almost all Civil Engineering infrastructure projects have an impact on the environment as well. The most traditional method of analyzing environmental impacts of projects is through a Life Cycle Analysis, which tracks emissions such as Carbon Dioxide (CO_2) or Greenhouse Gasses through the production, construction, use, and end of life of projects. However, there are several other tools that can be used, including Ecological Footprint and Planet Boundary. These two tools are introduced with discussion on how to incorporate them into pavement design.

The concept of Ecological Footprint, or EF, originated in the early 1990s. The concept is based on nature's capital, and the fact that certain needs are necessary for human life. These needs include healthy food, energy for mobility and heat, fresh air, clean water, fiber for paper, and clothing and shelter. The goal of the EF was to develop a scientifically sound calculation and that could relate to clear policy objectives. In addition, it needed a clear interpretation, to be understandable to non-scientists, and to cover the functioning of a system as a whole. Finally, the metrics had to be based on parameters that are stable over long periods of time so that minor or local fluctuations would not compromise quantifications.

The concept of Planet Boundary was first proposed in 2009 and is defined as a "safe operating space" for humanity. According to this theory, if human activities stay within the safe space, the earth is able to absorb the human activities with no long-term harm to the environment; however, if the human activities move outside of the safe space, the Planet Boundary theory states that long-term harm may occur to the environment. These spaces are associated with the earth's biophysical subsystems and processes.

1 SUSTAINABILITY BACKGROUND

1.1 *What is sustainability – the United Nations*

The term "sustainability" is currently very popular. Both the public and private sector realize the benefits of protecting the future while succeeding in the present. In the present, sustainability is most often defined as incorporating three pillars into design: economics, environmental, and social. One path of this definition of the three pillars was developed by the United Nations (UN) through a series of conferences and forums.

The first significant milestone for sustainability within the UN was the World Conservation Strategy, developed in 1980 (IUCN, 1980). This strategy revolved around three goals that focused on the concept of protecting the environment, with terms such as ecological processes, life support systems, genetic diversity, species, and ecosystems. Seven years later the UN released the Brundtland Commission Report, which is probably the most recognizable milestone in the UN's sustainability development (Brundtland, 1987). The primary theme of the Brundtland Commission reads that sustainability "meets the needs of the present without compromising the ability of future generations to meet their own needs." This theme is independent of protecting the environment, but the concept of the environment is still woven into the fabric of the theme. In 2002 the UN hosted a World Summit on Sustainable Development, which for the first time defined what are called the three pillars of sustainability: economics, environment, and social (UN, 2002). While the UN has continued to explore the concept of sustainably, the 2002 summit provided the foundation of the three pillars, which are generally accepted as the standard definition of sustainably. It is through this definition that organizations much closer to the pavement community, such as the American Society of Civil Engineers (ASCE), have also embraced the concept of sustainability.

1.2 *What is sustainably – the American Society of Civil Engineers (ASCE)*

ASCE was founded in 1852, is the oldest engineering society in the United States, and has more than 150,000 members across 177 countries. ASCE defines sustainability as: "A set of environmental, economic and social conditions in which all of society has the capacity and opportunity to maintain and improve its quality of life indefinitely without degrading the quantity, quality or availability of natural, economic, and social resources." This definition clearly incorporates the three pillars of sustainability (economics, environment, social) as developed by the UN. Not only does ASCE have a formal definition of sustainably, but the ASCE Code of Ethics (ASCE, 2006) mentions sustainably on multiple occasions.

The ASCE Code of Ethics has four fundamental principles and seven fundamental canons. Sustainability is mentioned at the very beginning of the Code in the first principle: "using [engineer's] knowledge and skill for the enhancement of human welfare and the environment." This principle directly addresses two of the three pillars of sustainability, environment and social. In addition to the first principle, sustainability is mentioned in several of the seven canons. Canon 1 says "engineers shall… strive to comply with the principles of sustainable development." Canon 1 also states that engineers need to work for the advancement of safety, health, and well-being of their communities (social pillar) and the protection of the environment (environment pillar). Canon 3 continues the sustainability theme by asking engineers to endeavor to extend public knowledge of engineering and suitable development (social pillar). By incorporating sustainably concepts into both the principles and canons, ASCE enforces the commitment of the civil engineering community in understanding and incorporating sustainable practices.

1.3 *Quantifying and qualifying sustainability*

Using the concept of the three pillars of sustainability, economic, environment, and social, many quantifications and qualifications have been developed. The economic pillar is by far the most developed, with concepts such as Life Cycle Cost Analysis, present/future/annual worth, rate of return, and benefit/cost ratio. On the other end of the spectrum, the social pillar is the least developed. While tools are available, such as the Oxfam Doughnut, Human Development Index, and Social Impact Assessment, there are limited metrics that either quantify or qualify the social aspect of civil engineering projects (Braham and Moon, 2016).

The development of the environment pillar lies somewhere in between the economic and social pillars. There has been significant work performed on Life Cycle Analysis (LCA). For example, LCA has been utilized to compare flexible pavement to rigid pavement (Weiland & Muench, 2010), pavement life (Harvey *et al.*, 2016), and has provided the foundation for a Pavement Life Cycle Assessment Workshop held at the University of California Davis in May, 2010. Other tools have been developed in roadways as well, such as the Greenroads rating system. Greenroads, founded as a company in summer 2010 by Jeralee Anderson and Steve Muench, has eleven categories of project requirements and thirty-seven voluntary requirements. Project requirements that revolve around environment concepts range from runoff flow control to ecological connectivity to environmental training (Anderson & Muench, 2013). Finally, tools have been utilized in order to better capture environmental influences of pavements through Environmental Impact Assessments (EIA) (Moretti *et al.*, 2013). EIAs allow for a systemic analysis of the impact of pavement design, production, construction, use, and end of life on the environment.

While tools such as LCA, Greenroads, and EIA have been utilized for pavements, there are two tools that have been developed that have not been utilized for pavements. These tools are Ecological Footprint and Planet Boundary. This report will provide an overview of these tools, along with recommendations for how to potentially leverage these tools to better understand the environmental impact of pavements.

2 ECOLOGICAL FOOTPRINT

Ecological Footprint, or EF, was developed at the University of British Colombia in the early 1990s (Wackernagel, 1994). The concept is based on nature's capital, and the fact that certain needs are necessary for human life. These needs include healthy food, energy for mobility and heat, fresh air, clean water, fiber for paper, and clothing and shelter. The goal of the EF was twofold: develop a scientifically sound calculation and clearly relate to policy objectives. In addition, it needed to have clear interpretation, be understandable to non-scientists, and cover the functioning of a whole system. Finally, the metrics had to be based on parameters that are stable over long periods of time so that local or other minor fluctuations would not compromise quantifications.

EF is based on taking specific economy or activity's energy needs, and converting that energy and matter to land and water needs. In short, this is determined through a five step calculation. First, the consumption of either a city, region, state, or country is calculated and split into food, housing, transportation, consumer goods, and services. Second, land area of the analysis zone is appropriated into either cropland, grazing, forest, fishing ground, carbon footprint, or built-up land. Cropland is land available to produce food and fiber for human consumption, feed for livestock, oil crops, and rubber. Grazing is land that can raise livestock for meat, dairy, hide, and wool products. Forest provides the land for lumber, pulp, timber products, and wood for fuel, while fishing ground covers the primary production area required to support the fish and seafood caught. While forest is one category for providing wood products, the carbon footprint is the amount of forest land required to absorb CO_2 emissions. Finally, the last category is built-up land, which is the area of land covered by human infrastructure. Once the consumption and land use is identified, both resource and waste flow streams are calculated, which is the third step in the calculation. The fourth step is the construction of a consumption/land-use matrix. This matrix shows all categories of both consumption and land use and indicates where there is not enough land for certain consumptions as well as which land is excess land. The deficiencies give numbers greater than one while the excess give numbers less than one. The fifth and final step sums all of the numbers and provides an estimate of EF for a region. These five steps are summarized in Table 1.

Table 1. Five-step calculation for Ecological Footprint

Step	**Description of each step**
One	Consumption of food, housing, transportation, consumer goods, and services determined
Two	Land area appropriated into cropland, grazing, forest, fishing ground, carbon footprint, or built-up land
Three	Resource and waste flow streams calculated
Four	Construction of a consumption/land-use matrix
Five	Sum all of the numbers, provide an estimate of EF for a region

When considering EF from a country level, it is interesting to note that the highest EF countries are from the Middle East according to a 2010 report published by the Global Footprint Network (Ewing *et al.*, 2010). This report states that the United Arab Emirates (UAE) and Qatar were producing EFs greater than 10.0 global hectares per person. This number states that if every person in the world was living the standard of living of the average UAE citizen living on UAE's resources, we would need over ten earths to sustain life. The next grouping down consists of western, fully developed countries, which required approximately 5-8 earths to maintain their standard of living. The list continues down through second world, developing, and third world countries. According to the report, it is interesting to note that the countries requiring less than one earth is quite diverse both geographically and socio-economically, from the Democratic Republic of the Congo (population 63 million) to Bangladesh (population 158 million) to Puerto Rico (population 4 million).

One study that has been performed is using impervious surfaces, which includes pavements, as a proxy measure for EF (Sutton *et al.*, 2009). Since it is relatively easy to calculate constructed areas per person from satellite images, it is convenient to use this measurement to determine EF instead of more difficult measures such as fiber and fuel wood consumption, two traditional inputs into an EF analysis. By using aerial photographs from thirteen cities in the United States, impervious surfaces (such as rooftops, sidewalks, parking lots, and roadways) were identified and the ratio of impervious surfaces to pervious surfaces (such as lawns, parks, and golf courses) over 100 random points across the image were classified. An R^2 value of 0.78 was found between the impervious surfaces and the EF, providing decent correlation between percentage of impervious surfaces and EF. Sutton *et al.* (2012) continued work in this area by developing a monetary correlation between impervious surfaces and consumption of ecosystem services.

There are, of course, some drawbacks to the EF concepts. First, the physical consumption-land conversion factor weights do not necessarily correspond to social weights. The analysis focuses one hundred percent on the metrics at hand, but do not consider the social choices people have to make. Second, the EF does not distinguish between sustainable and unsustainable use of land, only that land is being consumed. Therefore, forest could be clear-cut or sustainably harvested, two processes to extract wood from nature, but the EF would treat these practices as the same. A third criticism is that in the EF model there are many options to compensate for CO_2 emission and CO_2 assimilation, such as by forest, chemosynthesis, and autotrophs. However, the EF model only compensates for CO_2 emission and assimilation by forest, neglecting the other options. A fourth criticism is that there is a significant correlation between population density and resource endowment. As populations move away from rural living to urban living, the EF will increase significantly, especially as the analysis zone shrinks. This artificially inflates the EF of urban areas while perhaps underestimates the true EF of rural areas. The fifth and final criticism discussed here is that EF is hard to use as a planning device. While it is noble to attempt to decrease the EF, there are few tangible concepts that agencies can focus on to begin the reduction, making it difficult to leverage. While no measure is truly perfect, these deficiencies have led to the development of other metrics, including the Planet Boundary.

3 PLANET BOUNDARY

Planet Boundary as a tool to evaluate environmental impact was first proposed in 2009 and is defined as a “safe operating space” for humanity (Rockström *et al.*, 2009a). According to this theory, if human activities stay within the safe space, the earth is able to absorb the human activities with no long-term harm to the environment; however, if the human activities move outside of the safe space, the Planet Boundary theory states that long-term harm may occur to the environment. These spaces are associated with the earth’s biophysical subsystems and processes.

A major premise of Planet Boundary theory is that the environment has been unusually stable for past 10,000 years, commonly referred to as the Holocene period. During this time, the earth’s temperatures, freshwater availability, and biogeochemical flows have all stayed within a narrow, stable range (Rockström *et al.*, 2009b). However, with the beginning of the Anthropocene period, which is believed to have started after Industrial Revolution in the 1800s, human influence may have begun to damage the system that keeps earth within Holocene state according to Planet Boundary theory. This system was divided into nine subsystems, eight of which have been quantified. The nine subsystems have some overlap with both concepts learned in the LCA section and the EF section, but they also venture into new areas. The nine Plant Boundary subsystems are summarized and quantified in Table 2 for both 2009 and 2015 (Steffen *et al.*, 2015), with a brief discussion following (Note: the nitrogen and phosphorus cycle are combined into one process called biogeochemical flows).

Table 2. Planet Boundary subsystems

Earth-system process subsystems	Proposed boundary	2009 Status	2015 Status
Climate change (ppm CO_2)	350	387	396.5
Rate of biodiversity loss (extinctions per millions species-years)	10	>100	100-1000
Biogeochemical flows: Nitrogen cycle (millions tons/yr)	62-82	121	150
Biogeochemical flows: Phosphorus cycle (millions tons/yr)	6.2-11.2	8.5-9.5	14-22
Stratospheric ozone depletion (Dobson unit, DU)	276	283	As low as 200
Ocean acidification (carbonate ion concentration)	>2.75	2.90	2.89
Global freshwater use (km^3/yr)	4,000	2,600	2,600
Change in land use (percentage)	75	11.7	62
Atmospheric aerosol loading (aerosol optical depth)	0.25-0.50	Not determined	0.30
Chemical pollution	Not determined	Not determined	Not determined

In Table 2, climate change is quantified by measuring the atmospheric carbon dioxide concentration, with units of parts per million by volume. Another quantification discussed for climate change was the change in radiative forcing. This radiative forcing was listed at 1.5 in 2009 and is set at 1.0 for the boundary. Additionally, the rate of biodiversity loss was measured by the extinction rate, and is the number of species per million species per year lost. The nitrogen cycle is the amount of N_2 removed from the atmosphere for human use in millions of tons per year, while the phosphorus cycle is the quantity of P flowing into the oceans per year, in millions of tons. The stratospheric ozone depletion is the concentration of ozone, using the Dobson unit, while the global freshwater use is the consumption of freshwater by humans per year, in kilometers cubed. The change in land use is simply the percentage of global land cover converted to cropland from the natural state of the land. The atmospheric aerosol loading is the particulate concentration in the atmosphere on a regional basis, and the chemical pollution, which include emissions of everything from organic pollutants, to plastics, to heavily metals, and nuclear waste, has not yet been quantified. Figure 1 shows a visual image of the processes.

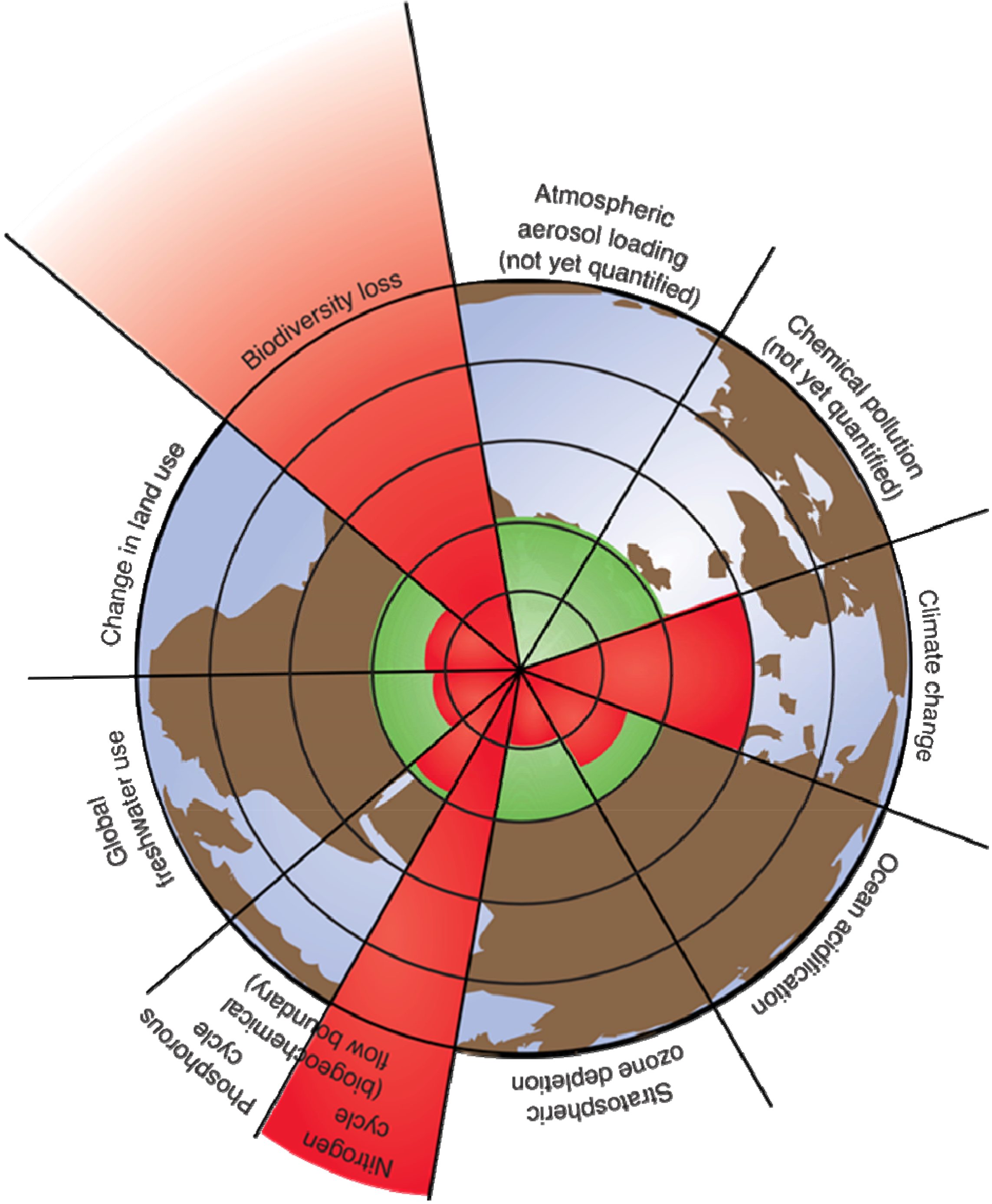

Figure 1 – Planet Boundary (credit: Azote Images/Stockholm Resilience Centre)

Like the EF, Planet Boundary theory has some pros and cons, but it is another tool that potentially can be used to quantify the influence of Civil Engineering infrastructure on the environment. At this point, no research has explicitly examined the influence of pavements on Planet Boundary, but it appears that the tool has promise in both pavements and other Civil Engineering applications.

4 CONCLUSIONS

The United Nations and the American Society of Civil Engineers have made sustainability a cornerstone of their organizations. These groups partially define sustainability as revolving around three pillars: economic, environment, and social. Unlike the variety of established tools available for the economic pillar of sustainability, there is only one well established tool to quantify the environmental aspects of sustainability, the Life Cycle Assessment (LCA). While other concepts are available, such as Ecological Footprint and Planet Boundary, these have not been implemented across a wide range of civil engineering applications. Ecological Footprint finds the relationship between human consumption, in the form of food, housing, transportation, consumer goods, and services and the land area available to produce these consumables, including cropland, grazing, forest, fishing ground, carbon footprint, and built-up land. While there have been no research project directly relating pavements to Ecological Footprints, relationships between impervious surfaces and Ecological Footprint have been developed and are relatively well correlated. Planet Boundary has established safe operating spaces in nine earth system processes (including concepts such as climate change, biodiversity loss, and ocean acidification). While there has been no direct research in establishing the impact of pavements on Planet Boundary, the concepts are conducive to exploring the application. Overall, there is promise in both Ecological Footprint and Planet Boundary, and these two tools may become more salient in the future of pavement reserach.

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