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Global Challenges, Geosynthetic Solutions and Counting Carbon

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Abstract

The earth is experiencing unprecedented change driven by increasing population, industrialisation and urbanisation. This is leading to rapid climate change and scarcity of resources. There is growing agreement globally of the need to deliver sustainable development to improve the lives of millions of people in low and middle income countries through provision of clean water, sanitation, energy and transport solutions. The response of the international community to this challenge is via the United Nations programme (published in January 2016), which establishes 17 Sustainable Development Goals (SDG) including response to climate change. These SDG will guide decisions taken by nations and organisations over the next 15 years. This paper is the written version of the opening keynote lecture delivered to the 3rd Pan American Conference on Geosynthetics in Miami Beach, USA, in April 2016; it considers the role that geosynthetics can make in achieving the SDG. Scientific evidence for climate change is presented and the value and uncertainty in available climate change information is discussed to inform its use in design. International agreements on reducing greenhouse gas emissions are based on country specific action plans for mitigation and adaptation against climate change, and the potential for geosynthetics to help achieve these targets is identified. Finally, approaches for calculating embodied carbon for solutions incorporating geosynthetics are introduced and case studies that provide evidence for the 'sustainability' case for geosynthetics are summarised. The geosynthetics community is challenged to play a leading role in helping to deliver the SDG and hence a better future for populations world-wide.

Key words: Geosynthetics, global challenges, development goals, climate change, sustainability, carbon footprint, life cycle analysis

1 INTRODUCTION

This paper is the written version of the opening keynote lecture delivered to the 3rd Pan American Conference on Geosynthetics in Miami Beach, USA, in April 2016. The paper aims to stimulate thinking and discussion on the global challenges that society face and how geosynthetics can help contribute to sustainable global development, including response to a changing climate. The paper does not focus on solutions using specific geosynthetic materials or design approaches as there are numerous sources of excellent advice on such measures in published papers, standards and industry reports. However, there are moral and strong business cases to consider the high level drivers of global change and to question how as individuals and collectively as a geosynthetics industry, these challenges can be meet.

The paper uses the global challenge of delivering sustainable development as the framework for the discussion. After providing a very brief overview of geosynthetic materials and solutions, it summarises the United Nations Global Sustainable Development Goals (United Nations, 2015a), which encompass economic development, social development and environmental protection for future generations. As the key driver for much of the legislation and changes in behaviour world-wide, climate change forecasts and the international response are detailed, including mitigation opportunities and adaptation solutions. As a specific example, the paper considers approaches used for calculating embodied carbon for solutions incorporating geosynthetics and summaries state-of-the-art work that is providing evidence for the ‘sustainability’ case for using geosynthetics. The paper challenges readers to help make a difference to the world in which we live.

2 SUSTAINABLE DEVELOPMENT

The key question faced by the population of the earth is whether sustainable global development is achievable as low and middle income countries strive to improve their standard of living through delivery of infrastructure to provide critical life lines for people (e.g. safe places to live, clean water, food, mobility and energy)? This leads to a secondary question: Does the geosynthetics community have a role to play in delivering sustainable development? It is widely acknowledged that the current model of global development is unsustainable. If low and middle income countries attempt to replicate the approach and forms of infrastructure that have developed in high income countries in the last 200 years, this will lead to exhaustion of natural resources and generation of greenhouse gas (GHG) levels (i.e. of which CO_2 is the most prevalent and along with methane the most important) that will cause irreversible climate change and adverse impacts to populations across the globe. Therefore, in simple terms the global aim is to deliver “development that meets the needs of the present without compromising the ability of future generations to meet their own needs” (Brundtland, 1987). Although a more complete definition uses the principle of *The Three Pillars of Sustainability* and for the complete sustainability problem to be solved the three pillars of social, environmental, and economic sustainability must each be sustainable. It should be noted that this paper primarily considers environmental sustainability.

3 USES OF GEOSYNTHETICS

Civil engineers are at the forefront of efforts to achieve sustainable development; they can transform communities and deliver transformative improvements to people’s quality of life. One of the tools available to an engineer is the family of materials defined as geosynthetics and their varied applications. Geosynthetics are planar products manufactured from polymeric material used with soil, rock, earth, or other geotechnical engineering related material as an integral part of a construction project, structure, or system. Geosynthetics are important for sustainable development because as noted by Koerner (2012) they:

- Generally replace often scarce raw material resources;
- Can replace difficult designs using soil and other materials;
- Can make previously impossible designs possible;
- Are invariably cost competitive against alternative solutions; and
- Their carbon footprint is very much lower than alternative solutions.

As a reminder of the many roles and uses of geosynthetics, Figure 1 uses pictograms to summarise their core functions: Separation; Filtration; Drainage; Reinforcement; Solid and fluid/gas containment; and Erosion control. The reader should keep these functions in mind as key global challenges are introduced and consider how specific products, construction methods, analysis techniques and designs approaches do and could increasingly make a difference in a wide range of key development sectors: Agriculture; Water treatment and supply; Resource recovery; Waste containment and treatment; Transport infrastructure: Road, rail, waterway, aviation; Energy: Generation and supply; Flood control; and Ecosystem protection and management.

It is also relevant to acknowledge the sustained impact of activities conducted over the last five decades under the auspices of the International Geosynthetics Society (IGS) (2016a), which combines a learned society and commercial representation. The IGS has helped to produce a mature industry that can deliver materials and solutions across these diverse sectors world-wide and a

Society that is fit to play a substantial role in delivering sustainable development. Applications and solutions are supported by established codes of practice and design approaches, and informed by rigorously peer reviewed papers in the Society's journals (Geosynthetics International, and Geotextiles and Geomembranes), and many tens of conference proceedings. The current status of the industry is due to a combination of the diligent and sustained work done by the IGS Council, National Committees, Corporate Sponsors and individual members world-wide sustained over many years.

The overarching philosophy for employing geosynthetics in any solution is that "appropriate use" is fundamental. Geosynthetic based designs have historically been compared to solutions described as "traditional" or "conventional", however this is no longer helpful as this implies that geosynthetics are still new and untested, which is no longer the case, rather than denoting that they are novel and exciting, which is often the intent. Continued education of clients and construction professionals is critically important if the benefits of geosynthetics are to be acknowledged widely. A good example of educational material is the IGS sustainability movie (IGS, 2016b) that has been designed to inform and educate clients and non-specialist about using geosy**n**thetics to achieve sustainable development. Another important activity by the IGS is the Educate the Educator initiative. The aim is to educate academics and encourage them to include geosynthetics in the core curriculum of engineering courses world-wide. The first event was held in Argentina in May 2013, with follow up events in the USA, China and Turkey, among others. The plan is to extend and expand such training activities around the world so that the benefits of using geosynthetics are disseminated widely.

4 SUSTAINABLE DEVELOPMENT GOALS

It is pertinent to consider the scale of the challenge facing the global population at the present time. World Health Organization and UNICEF Joint Monitoring Programme (2015) report that the global population is approximately 7.4 Billion and of this, 1 in 10 people lack access to safe water (a total equivalent to twice the population of the USA), women and children spend 125 million hours each day collecting water, 1 in 3 people lack access to a toilet and every 90 seconds a child dies from a water related disease. 50% of world resources are used to create infrastructure and it has been estimated that $57 trillion investment is needed in infrastructure before 2030. At the same time, populations are increasingly vulnerable to natural disasters as a result of global change (i.e. climate change, urbanisation and land use change) (World Health Organization and UNICEF Joint Monitoring Programme, 2015). The response of the international community is via the United Nations programme - *Transforming our world: The 2030 Agenda for Sustainable Development* (United Nations, 2015a), which came into effect in January 2016. This programme establishes 17 Sustainable

Development Goals, which will be used to guide decisions taken by nations and organisations over the next 15 years (United Nations, 2015a). These high level national decisions will focus the scale and priorities for funding, with each country facing specific range and combination of challenges. The 17 development goals are depicted in Figure 2.

Although the majority of the goals have aspects related to the availability and operation of appropriate infrastructure, of particular relevance and importance to the focus of this paper are:

- Goal 6 - Clean water and sanitation: Ensure available and sustainable management of water and sanitation for all. Collection, storage, treatment and delivery of clean water, and storage, treatment, minimisation and safe disposal of human waste.
- Goal 9 - Industry, innovation and infrastructure: Facilitate sustainable and resilient infrastructure development through enhanced technological, technical and financial support, with affordability being critical.
- Goal 12 - Responsible consumption and production: Deliver sustainable management and efficient use of natural resources including via increased prevention, reduction, recycling and reuse of waste.
- Goal 13 - Climate action: Take urgent action to combat climate change and its impacts, including strengthening resilience and adaptive capacity to climate-related hazards and natural disasters in all countries.
- Goal 17 – Partnerships for the goals: Strengthen the means of implementation and revitalize the Global Partnership for Sustainable Development, including transfer of appropriate technology, capacity building and trade.

There are opportunities for geosynthetic solutions to play a role in achieving each of these development goals.

5 CLIMATE CHANGE

5.1 Context

Climate change is of overarching concern as it impacts on all of the development goals. Those working to deliver sustainable solutions must do so in the context of the climate change projections as these provide both drivers and a framework within which future infrastructure should be designed and will be operated. Failure to deliver infrastructure that mitigates climate change and/or delivers adaptation solutions, will condemn millions of people to a future quality of life that is not improved, and may even deteriorate, and the goals will not be achieved. The authors have experience using climate change information to investigate the impacts of projected change on critical infrastructure (e.g. Dijkstra *et al.* 2014). This experience investigating and questioning the science behind the headlines reported in the media has enabled a view to be established on both the rigour and usefulness of information currently available. This is shared in this paper as it is of critical importance that designers understand the context of their solutions and the use that can be made of climate change information.

5.2 Climate change trends: Past and future

Although people still debate the causes of climate change and the media continue to report the views of groups who *believe* (Section 5.5) that climate change is not occurring, the most recent Intergovernmental Panel on Climate Change (IPCC) report in 2014, the 5th in the series, presents unequivocal evidence that the climate system is warming (IPPC 2014). Since the 1950s many of the observed changes are unprecedented over decades to millennia and it is very likely that human influence has been the dominant cause of the observed global warning since the mid-20th century. The report concludes that we (the world's population) must reduce future greenhouse gas emissions to better manage the impacts of climate change on the environment, economy and society. As an example of the changes that are already occurring, global temperatures for January to September 2016 have been about 0.88°C above the average for the 1961-1990 reference period (World Meteorological Organization, 2016). This is the value averaged over the entire earth's surface including land and oceans and not a site specific measurement. Figure 3 shows annual variation in global average temperatures illustrating the warming trend of the last century (IPPC, 2014, Figure SPM.1). The IPPC (2014) report warns that in the future, continued GHG emissions will cause further warming and changes in all components of the climate. Global surface temperature change for the end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 period and contrasts in precipitation between seasons will increase.

5.3 Impacts of climate change

IPPC (2014) present detailed assessments of impacts for all regions of the earth and across a range of sectors that have already been experienced and that can be attributed to climate change. As an example, Figure 4 taken from IPCC (2014) summarises the reported impacts from climate change globally. The evidence is taken from published peer review papers reporting scientific studies. There are already measureable impacts in physical, biological and human/managed systems. In Figure 4, confidence that climate change is the cause is indicated by the height of the column, the colour denotes the type of system and the cartoon the specific impact (e.g. the high confidence in (blue) impact on rivers, lakes, floods/droughts in North and South Americas).

As an example, projected temperature and precipitation changes taken from IPPC (2014) are shown in Figure 5 for both temperature and precipitation. Change in the period 1986 to 2005 is on the left and the projected changes 2061 to 2100 are shown on the right. All areas are projected to get warmer by a number of degrees, but precipitation is more mixed with some areas getting wetter and some dryer. However, note that these are average changes and variation of extremes is expected to be larger.

5.4 Causes and uncertainty

One of the main battle grounds over climate change is whether the earth is experiencing natural variation in the earth's weather comparable to times in the past, or whether the rate of change is being driven by anthropogenic factors. The IPPC report (2014) is unequivocal that anthropogenic factors are the cause of the observed recent changes. Figure 6 compares temperature modelling output of recent climate both including and excluding anthropogenic factors. Although model outputs have a range (i.e. width of blue band excluding anthropogenic and pink band including these factors), only the models including GHGs generated by anthropogenic activities (i.e. pink) can replicate the measured behaviour of physical systems (e.g. temperature and sea ice) in the last few decades. Actual measured behaviour denoted by the thick black line is consistently within the pink and not the blue bands of model outputs.

However, despite the clarity and consistency of the climate change projections there is considerable uncertainty due to a number of factors. Firstly, the level of future global GHG emissions is unknown so the projections use a family of four emission scenarios, the likelihood of each being dependent on the success or otherwise of climate change agreements and hence of plans to deliver the sustainable development goals. Although the relative likelihood of emissions scenarios is unknown, climate change is almost independent of emissions scenario in the next few decades (IPPC, 2014) and, therefore, change will still occur even if GHG emissions are drastically cut in the near future, which is highly unlikely. A second important source of uncertainty in projections is due to the natural variability of weather. This natural variability is incorporated in projections by running models with the same emissions but different initial conditions multiple times. Thirdly, is modelling uncertainty that is due to our current incomplete understanding of climate processes and inability to model them perfectly. This is incorporated in projections by aggregating the outputs from many models (e.g. produced by national bodies from around the world responsible for climate change projections and research organisations) and multiple runs. This detailed consideration of uncertainty informs the projections published by IPPC and also those produced by other bodies. For example, the UK climate change projections UKCP09 (Murphy *et al*., 2009) are presented in a probabilistic framework.

Despite this uncertainty, a consistent message provided by the numerous modelled climate change projections is that variability and occurrence of extreme events will increase, with standard deviation of precipitation and temperature events forecast to change two times that of mean values (IPPC, 2014).

5.5 Confidence in climate change projections

IPCC's 5th Assessment Report (2014) provides a comprehensive assessment of the physical science basis of climate change. It comprises 14 chapters, has multiple annexes and supplementary material, 800 scientists have contributed to the report and many scientific bodies around the world have reviewed it. In contrast, there is no significant body of evidence to contradict the findings of the report. However, as noted in Section 5.2, there are still vociferous climate change deniers driven by a range of motivations including scientific, theological and political. It should be recognised that the IPCC (2014) conclusions are based on the scientific method: Systematic observation, measurement and experiment, and the formulation, testing and modification of hypotheses.

5.6 Global action on climate change

The 2015 United Nations Framework Convention on Climate Change held in Paris, December 2015 (United Nations 2015b), delivered the latest in a series of climate change agreements in which signatory counties agreed to deal with greenhouse gas emissions mitigation, adaptation and finance starting in the year 2020. At this event a global agreement was reached by an unprecedented 196 parties (i.e. countries and confederations such as the European Union) on 12th December 2015. The agreement set a goal of limiting global warming to less than 2°C. As of December 2016, 194 parties had signed the treaty, 116 of which have ratified it. By October 2016 there were enough countries that had ratified the agreement for it to enter into force, and it went into effect on 4th November 2016. However, given the change in political leadership in the USA in January 2017, who are one of the highest GHG emitters, to an administration that is sceptical about the causes of climate change, there is growing uncertainty around the likely effectiveness of the treaty given that at is core is a requirement to develop, disseminate and adopt practices that deliver sustainable development.

Despite acknowledged limitations of the Paris agreement, it is a break through agreement with all major counties initially included. The target of not exceeding 2°C in comparison to pre-industrial level is to be achieved by controlling anthropogenic GHG emissions. A significant aspect of the agreement is that it was made possible because 186 countries published action plans prior to the Paris convention. Each plan sets out the way in which the country intends to reduce their GHG emissions. However, a United Nations (2016b) evaluation of these showed that global warming would still be between 2.7°C and 3°C (i.e. above the critical threshold set by scientists). Therefore, the Paris agreement asks all countries to review these contributions every five years from 2020 onwards. One of the main principles of the climate negotiations was that countries have common but differentiated responsibilities when it comes to climate change, in particular depending on their wealth. The agreement establishes an obligation for industrialized countries to provide climate finance for poor countries, while developing countries are invited to contribute on a voluntary basis.

5.7 Actions to make a difference

Two categories of action are required to tackle climate change and its effects: Mitigation to reduce greenhouse gas emissions and adaptation. The latter is to be achieved through implementing policies and measures to adapt to climate change and to build resilience of populations, ecosystems, infrastructure and production systems by reducing vulnerability. Mitigation by Governments is at the heart of contributions to reduce GHG emissions. Mitigation objectives are at the national economic level and include all sectors, with energy, industrial processes, agriculture, waste as well as forests and land use covered by contributions. As detailed in Section 8, geosynthetics can make a contribution to mitigation by reducing carbon emissions from constructing and operating infrastructure. However, they can also make a significant contribution to adaptation, specifically in resilience of communities and infrastructure to extreme climate disasters such as flooding, landslides and drought.

As a case study, Mexico´s climate change action plan (United Nations, 2015c) reports that its' geographic characteristics make it a highly vulnerable country to impacts of climate change as its location, latitude and topography increase exposure to extreme hydro meteorological events. In the last 50 years, Mexico has experienced measurable changes in temperature and mean precipitation. The country has become warmer, with an average temperature increase > 0.85°C and has experienced an increased number of extreme weather events such as tropical cyclones, floods and droughts. Climate change projections for Mexico indicate likely changes in the mean temperature of up to 2°C in the North in the next 25 years, and annual precipitation reduction is projected to be 10 to 20% across the country. 13% of municipalities are highly vulnerable to the adverse impacts of climate change including droughts, floods and landslides.

In response to these threats, Mexico's action plan for 2020-30 (United Nations, 2015c) includes relocating infrastructure from high-risk zones and incorporating adaptation criteria for public investment projects that include infrastructure. Effects of climate change are also to be routinely included in the planning, design, construction and operation of coastal tourism facilities, and work is in train to guarantee the security of dams and hydraulic infrastructure, communications and strategic transportation infrastructure. Adaptation strategies have been identified by the Government and many will provide opportunities for the geosynthetics industry. Areas identified where technology transfer could be of benefit for adaptation include:

- Information systems to monitor events in real time and enhance early warning systems (Smart infrastructure);
- Water technologies for savings, recycling, capture, irrigation and sustainable management for agriculture;
- Transportation technologies resilient to effects of climate change in particular for roads and rail transportation; and
- Technologies for the protection of coastal and river infrastructure.

While the scale of the challenge is somewhat daunting, examples exist of how high level global agreements are resulting in local and industry specific change. As part of the Kyoto Protocol (United Nations, 1998) produced following the 1997 Kyoto climate change conference, the European Union (EU) agreed to reduce GHG by 8% below 1990 levels by 2012. Post 2012 the EU adopted a policy to reduce GHG emissions by 20% from 1990 levels by 2020. In the UK, the Climate Change Act (United Kingdom Government, 2008) introduced a legally binding GHG emission reduction target of 80% by 2050. How to achieve this target is defined in *The Carbon Plan 2011, delivering a low carbon future* (United Kingdom Government, 2011). While the legislation is broad and no construction specific targets are set, transport, waste and resource efficiency are areas noted as being expected to contribute to meeting the UK targets for GHG emission reduction. There is a focus on zero carbon operation of infrastructure but no mention of savings during the construction phase. However, the UK construction industry has developed a strategy articulated in the report *Construction 2025* (United Kingdom Government, 2013), which identifies low carbon and sustainable construction as a strategic priority of the industry, with an ambition to reduce GHG emission by 50% by 2025. There is an expectation that GHG emission will be a criteria used to select construction solutions and all major projects have to have GHG evaluation as part of their environmental assessment.

6 A MEASURE of SUSTAINABILITY: COUNTING CARBON

There are numerous valid approaches that can be used to measure the sustainability of an engineering solution including social, environmental and economic aspects. However, because international agreements and targets are defined using GHG emissions, this is an obvious measure to use at the current time. As governments seek to fulfil the Paris climate change agreement targets, it is likely that industries, including construction, will be expected to deliver reductions in GHG emission. Therefore, the pragmatic approach is to concentrate on GHG emissions when championing geosynthetics as a sustainable solution, despite the plethora of other measures that could also be used (e.g. see Section 8.2).

Carbon footprint is a measure of total GHG emissions caused directly and indirectly by a person, organisation, event or product. It is measured in tonnes of carbon dioxide equivalent (tCO_2e). A carbon footprint can cover emissions over the whole life of a product, service or solution (i.e. including a construction solution) and embodied carbon (EC) is an indicator of cumulative carbon emissions used in the solution adopted. Figure 7 shows an example subdivision of a hypothetical material and processes contributing to the EC of an end product, such as a geosynthetic. It should be noted that sometimes Embodied Energy is reported in place of Embodied Carbon. Conversion between the two measures needs knowledge of the CO_2 emitted during generation of the energy used (DEFRA, 2013). This is country specific and hence is a challenging calculation to undertake as information on mixes of energy sources is sparse and this currently makes international comparisons difficult.

Comparison of calculated carbon footprints for alternative solutions can be used to inform selection of the most 'sustainable' option. A site-by site approach can consider project specifics such as: available materials on site and nearby; supply logistics; site layout; method of construction etc. Life Cycle Assessment (LCA) is a tool for measuring the environmental impact of products or systems over their lifetime. It can consider extraction of raw materials, through production, use, recycling and disposal of waste. LCA is often used to compare the impact of two competing products or systems, with the analysis process informed by ISO14040 (2006a) and ISO14044 (2006b) or other approved tools. LCA boundaries are clearly defined boundary conditions and are required to describe which parts of the material production, manufacture and deployment are taken into account in calculating the carbon footprint. Typically used LCA are shown in Figure 8 mapped against the stage of product manufacture and application.

There is a growing trend for product manufacturers (e.g. concrete, steel, geosynthetic) to develop in-house carbon calculators for quantifying LCA of products and designs that can be used for comparisons between alternative solutions. While this is a welcome development, in some cases these are perceived as being marketing tools and there is a danger that they will be considered unreliable, in part due to a lack of transparency of the method and material EC values employed. There is need for a geosynthetics industry standard approach endorsed by geosynthetic manufacturers and suppliers, recognised and trusted by construction organisations and clients.

7 EMBODIED CARBON FOR GEOSYNTHTETIC MATERIALS

The rigour of any LCA is based on the validity of material EC values employed and hence accurate embodied carbon data is required for geosynthetic materials. To date, the majority of studies reported in the literature for geosynthetics have used EC values from two published databases; the Inventory of Carbon & Energy (ICE) database (Hammond and Jones, 2011) and the European life cycle analysis database called ‘EcoInvent v3.3’ (e.g. EcoInvent Centre, 2016). However, neither includes geosynthetic product specific values with only generic plastic materials reported. This lack of geosynthetic product specific information has allowed advocates of ‘competitor’ solutions to question the rigour and accuracy of studies that show geosynthetic solutions to be more sustainable. However, recently published studies such as by Raja *et al.* (2015) add to information produced by manufacturers to provide EC for specific geosynthetic product ranges (e.g. non-woven geotextiles and geogrids). This information is improving the rigour of LCA analyses and comparisons.

8 LIFE CYCLE ASSESSMENT FOR GEOSYNTHETIC SOLUTIONS

8.1 Framework and calculation methods for project carbon footprint

To ensure the accuracy and impact of the case studies that compare EC of geosynthetic based and alternative construction solutions requires a consistent and robust CO_2 calculation framework. This ensures the validity and credibility of the results by comparing like for like activities with respect to CO_2 emissions generated. Figure 9 details the framework for a CO_2 assessment of a construction solution incorporating geosynthetics. The framework comprises five stages of analysis, however, depending on the LCA boundaries, Stages 4 and 5 may be omitted.

8.2 Example case studies

There is a growing body of literature detailing studies of the sustainability credentials for geosynthetic based solutions. These invariably use a derivation of the LCA approach introduced in Section 6 and all include comparisons with non-geosynthetic solutions. While all use EC as a measure, a subset also considers a wider range of criteria for a broader evaluation of sustainability including: Cumulative energy demand; photochemical ozone formation; particulate formation; acidification, eutrophication, land competition; and water use. The large majority use EC for the geosynthetic products taken either from the ICE database (Hammond and Jones, 2011) and earlier versions of the EcoInvent Centre (2016) databases with their consequent limitations as discussed in Section 7. In addition, the Heerten (2012) study uses EC data from the German Institution "Forschungsstelle für Energiewirtschaft e.V" (FFR). The number of case studies using product specific EC values is growing. A direct comparison between case studies is not possible because the type of study varies, with some using project level information and others defining functional units of a given application/solution, and in addition different ranges of LCA boundaries are employed; however general trends can be identified. A summary of the key attributes of the case studies is provided in Table 1 and brief details and key findings are provided below. It is likely that the number and scope of studies reported in the literature will increase significantly in the near future.

The UK Waste & Resources Action Programme (WRAP) published a report in 2010. The study details calculation of CO_2 for six case studies for a range of construction activities. LCA boundaries used are Cradle to Gate. IGS UK Members provided information. The case studies showed how the use of geosynthetics amongst other benefits can also reduce the amount of imported fill. This provided CO_2 savings from the embodied carbon emissions from quarrying of fresh fill as well as that from the transportation of these materials on and off site. The WRAP (2010) study delivered an accessible report with a very clear unambiguous conclusion that construction solutions incorporating geosynthetics led to significant cost and CO_2 savings. However, a limitation is that all six applications analysed are on reinforcement. Material embodied carbon values are taken from the available version of the ICE database (Hammond and Jones, 2011), including for the geosynthetics. Also, the relationship between embodied energy and embodied carbon for a given material is unclear.

The European Association of Geosynthetic Manufacturers (EAGM) commissioned a study of the environmental performance of solutions using commonly applied construction materials versus geosynthetics. The findings of the in depth analysis is reported by Stucki *et al.* (2011). The study provided comprehensive qualitative and quantitative information on the environmental performance of commonly applied construction materials (i.e. concrete) versus geosynthetics. The motivation was to provide EAGM members with findings that they could use to communicate benefits to customers, project clients and stakeholders. Four construction systems were considered: Filtration; foundation stabilisation; landfill drainage layer; and soil retaining wall. Life Cycle Impact assessment was extensive, considering eight environmental impact indicators listed above (e.g.

cumulative energy demand to water use). Hypothetical designs were used with the functional unit of the specific construction defined for each case. All cases considered were designed so that both the geosynthetic and conventional solutions were technically equivalent. The LCA encompassed Cradle to Grave. Data on EC of geosynthetics were obtained from EcoInvent database and EAGM members, however, limited details are provided of embodied carbon values used for the geosynthetic materials meaning that it is not possible to replicate the calculations. The key finding from this comprehensive study is that geosynthetic based solutions are consistently assessed as more ‘sustainable’ using a range of environmental performance measures.

Analysis of EC for a landfill capping project is reported by Raja *et al.* (2014). The study considers a one year capping project for an area of 9572 m^2 and compares the CO_2 emissions produced by the geosynthetic barrier design used and an alternative clay liner solution. The LCA boundaries are Cradle to End of Construction and the total CO_2 values include: embodied carbon in materials, transport of materials to site and construction process. All EC values for the materials are from the ICE database. The construction element focuses on compaction effort for the regulating layer and clay and considers: type of plant; thickness of layer; number of passes; and total layer thickness. It was noted that the comparison of alternative solutions was sensitive to the EC values used for excavating the clay soil (i.e. demonstrating that the ICE database has inconsistent EC values for materials other than plastics) and the transport distance for the fill. The findings from this study were consistent with others, demonstrating reduced CO_2 for geosynthetic based solutions compared to alternatives.

A rigorous and detailed study of an environmental assessment of earth retaining wall structures has been presented by Damians *et al.* (2016a). It describes fully the LCA methodology employed, which is comparable to the other studies reported in Table 1, and demonstrates the approach using: Two types of reinforced concrete wall (gravity and cantilever) and two reinforced soil (steel and polymeric), termed mechanically stabilised earth (MSE) walls. A sensitivity analysis considers four different heights: 3, 5, 10 and 15 metres of each wall type. Of particular use is the description of a numerical score based tool for quantifying environmental impacts and choosing between solutions. The LCA boundaries used are cradle to end of construction. Nine midpoint LCA environmental indicator categories are used to inform three end point damage categories (i.e. human health, ecosystem diversity and resources availability) and a weighted end point single score for each candidate solution (Figure 10). The MSE wall solutions consistently resulted in lower environmental impacts than gravity and cantilever wall solutions as measured by global warming potential, cumulative energy demand and considering six midpoint environmental indicator categories, all three endpoint damage categories and in terms of the endpoint single scores.

Damians *et al.* (2016b) then extend this study using a full sustainability assessment methodology to select the best option for the same candidate gravity and MSE walls used in Damians *et al.* (2016a). The study employs analyses carried out using the value integrated model for sustainable evaluations (Mives) methodology, which is based on value theory and multi-attribute assumptions. Damians *et al.* (2016a) explain how indicator issues are scored, weighted and aggregated to generate final numerical scores that allow solution options to be ranked. The final scores include an adjustment based on stakeholder preferences for the relative importance of the three sustainability pillars (i.e. environmental, economic and societal/functional). The results reported show that MSE wall solutions were most often the best option in each category compared to conventional gravity and cantilever wall solutions and, thus, most often they were the ‘best’ solution when scores from each pillar were aggregated to a final score. The methodology used by Damians *et al*. (2016b) for this full sustainability assessment is a powerful tool and will be of interest to those wishing to assess a wider range of geosynthetic solutions than the reinforcement applications considered to date and to consider all three sustainability pillars.

Heerten (2012) discusses reduction of climate-damaging gases (i.e. GHG) in geotechnical engineering by use of geosynthetics. This study compliments the results of the WRAP (2010) study. It compares classical construction techniques and geosynthetic construction alternatives and highlights the CO_2 savings of employing geosynthetic solutions in steep slope and road applications; however the study was again limited to the function of reinforcement. It considers the cumulated energy demand (CED) and climate related CO_2 emission for products, their transport to the manufacturer and to the site as well as installation. It concludes that a considerably smaller CED and CO_2 emission is shown for the geosynthetic alternatives for the range of applications reviewed.

Dixon *et al.* (2016) extend the number of EC studies for non-reinforcement geosynthetic applications employing geotextiles. An additional advance is the use of product specific EC values given by Raja *et al.* (2015) rather than using generic values for plastic from the established data bases detailed in Section 7. Three construction case studies are detailed with EC values calculated for both geotextile based and alternative solutions. Two of the cases consider protection and working platform applications respectively (based on a functional unit 1m^2 plan area, which is comparable to the approach taken by Stucki *et al.*, 2011) and cradle to site LCA boundary conditions. The influence of haulage distance for mineral components on total EC values is also considered. The third example compares EC for geosynthetic and soil based landfill capping solutions. The LCA boundary of cradle to end of construction is defined and a unit area of 1 ha area is considered to enable EC from construction activities to be meaningfully included. All three case studies demonstrated that solutions employing geosynthetics can result in significant reduction in EC and in addition they highlight the importance of comparing the EC for the whole construction solution and not simply the component products.

8.3 Summary: Counting carbon

Sustainability of materials and processes are commonly assessed by calculating the carbon emissions (CO_2) generated. This is a simplification but the ease of calculation encourages comparisons of solutions, makes outputs of assessments accessible, transparent and repeatable, and CO_2 savings can readily be counted towards industry, national and international targets. A common LCA framework for calculating embodied carbon of construction solutions that incorporate geosynthetics is now well established and there is a growing literature that demonstrates use of the approach and reports examples of assessments that conclude solutions incorporating geosynthetics are consistently more sustainable based on EC, but also using a range of other environmental indicators. Savings in EC are often realised because geosynthetics allow use of site derived often ‘marginal’ soils, thus reducing the amount of imported fill material; this minimises the transport related carbon emissions. A number of the studies have also concluded that geosynthetic based solutions also delivered significant cost savings. The methods outlined can be used to undertake site specific calculations that inform decisions on selection of construction approaches that contribute to sustainable practice. The need for sustainable construction solutions is a major opportunity for the geosynthetics industry, particularly given the cost savings that can also result.

9 ACHIEVING SUSTAINABILITY DEVELOPMENT GOALS

The breadth and scale of the global challenges are so large that it is tempting to conclude that the geosynthetics industry is unlikely to be able to make a difference. However, the doctrine of marginal gains describes how small incremental improvements add up to a significant improvement when aggregated. This philosophy was championed by Sir Dave Brailsford, Head of British Olympic Cycling Team, who believed a 1% improvement in many areas would be hugely significant. This approach was applied in British Cycling culminating in their domination of the medal tables at the 2008, 2012 and 2016 Olympics after many decades of poor performance. Arguably this philosophy is relevant for the ambition of reducing GHG using geosynthetic solutions. Given the scale of global infrastructure construction planned over the next 20 years, even small reductions will add up to make a very significant contribution to meeting national and global targets, which will help slow climate change and contribute to improving the lives of millions of people around the world. This is in addition to the important role that geosynthetic solutions will play as people and nations adapt to global change, including improved resilience to extremes of weather.

United Nations' Sustainable Development Goals challenge nations, organisations and citizens to make a difference to the lives of millions, including: providing access to clean water and sanitation; building and operating resilient infrastructure; and sustainable use of resources. Tackling the impacts of climate change underpins all of the development goals. Equal focus is needed to mitigate future GHG emissions and to develop adaptation solutions to meet impacts of the climate change that is already occurring and is locked into the future, irrespective of reductions in GHG that will result from the Paris agreement. By appropriate use of geosynthetics and considering the doctrine of marginal gains, the challenge for the geosynthetics community is to play a leading role in helping engineers deliver a better future for populations world-wide.

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Table 1 LCA case studies for geosynthetic solutions

Author/Type of study	**Solutions compared**	**LCA boundaries**	**Source of material EC**	**Sustainability measure**	**Key findings**
WRAP (2010)/Projects	• Environmental bund – gabion wall vs. reinforced soil • Road embankment – Imported stone vs. reinforced soil • Four retaining wall examples – Concrete/sheetpile and block walls vs. reinforced soil	Cradle-Gate	ICE	CO_2	Significant CO_2 (85 to 31%) and cost savings are related to reduced import and export of fill materials
Stucki *et al.* (2011)/ Functional units	• Pavement – Gravel vs. geotextile filter • Pavement – Fill/lime treatment vs. geogrid reinforcement • Landfill cap – Gravel vs. geocomposite drain • Retaining wall – Concrete vs. geogrid reinforced soil	Cradle-Grave (excluding maintenance and operation)	EcoInvent	CO_2 + 7 other indicators	Geosynthetic solutions have lower CO_2, plus lower environmental impact factors using a range of other measures. Savings are related to reduced import and export of fill materials. Uncertainty is considered.
Heerten (2012)/Projects	• Slope protection – Concrete vs. reinforced soil • Pavement – Lime treatment vs. geogrid reinforcement	Cradle-End of construction	FFR	CO_2, CH_4 & CED	GHG reductions using the geosynthetic solutions, with associated cost savings identified.
Raja *et al.* (2014)/ Projects	• Landfill cap - Clay vs. geomembrane & geotextile	Cradle-End of construction	ICE	CO_2	Geosynthetic solution generated a third CO_2 compared to the compacted clay barrier but the relative difference is sensitive to the distance to the clay fill source.
Damians et al. (2016a)/ Projects	• Retaining walls – Concrete (gravity and cantilevered vs. MSE walls (polymeric and steel)	Cradle-End of construction	EcoInvent	CO_2 + range of mid and end point indicators	MSE walls consistently produced lower environmental impacts across the range of mid-point, end point and single end point indicators.
Dixon et al. (2016)/ Functional units	• Protection – Sand vs. geotextile • Working platform – Gravel vs. geogrid reinforced reduced layer thickness • Landfill cap – Clay vs. geomembrane & geotextile	Cradle-Site Cradle-End of construction Cradle-End of construction	Material specific (Raja *et al.* (2015)	CO_2	Significant CO_2 savings on all three solutions dues to reduced import and export of fill, but the relative difference is sensitive to the distance to the fill source.

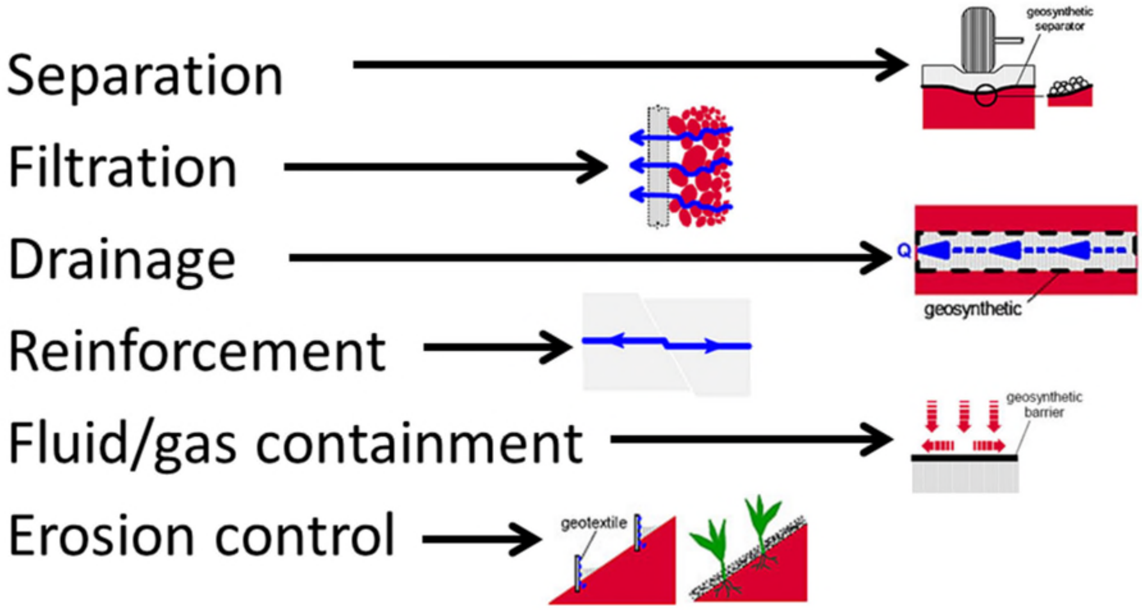

Figure 1 Core functions of geosynthetics

Figure 2 United Nation sustainability goals launched in January 2016 (United Nations, 2016a)

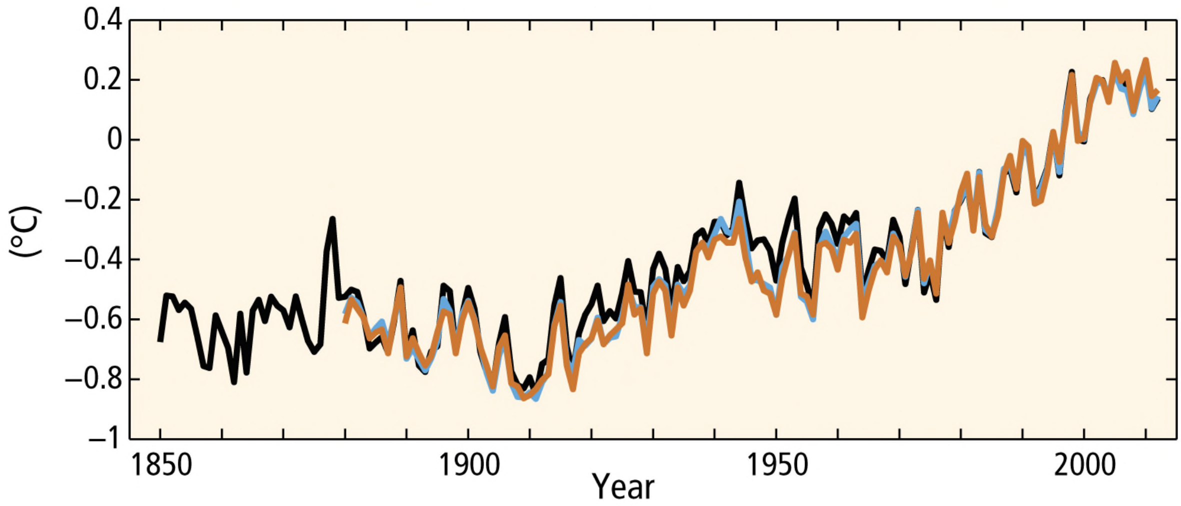

Figure 3 Annual measured variations in global average temperatures illustrating the warming trend of the last century (IPPC, 2014, Figure SPM.1)

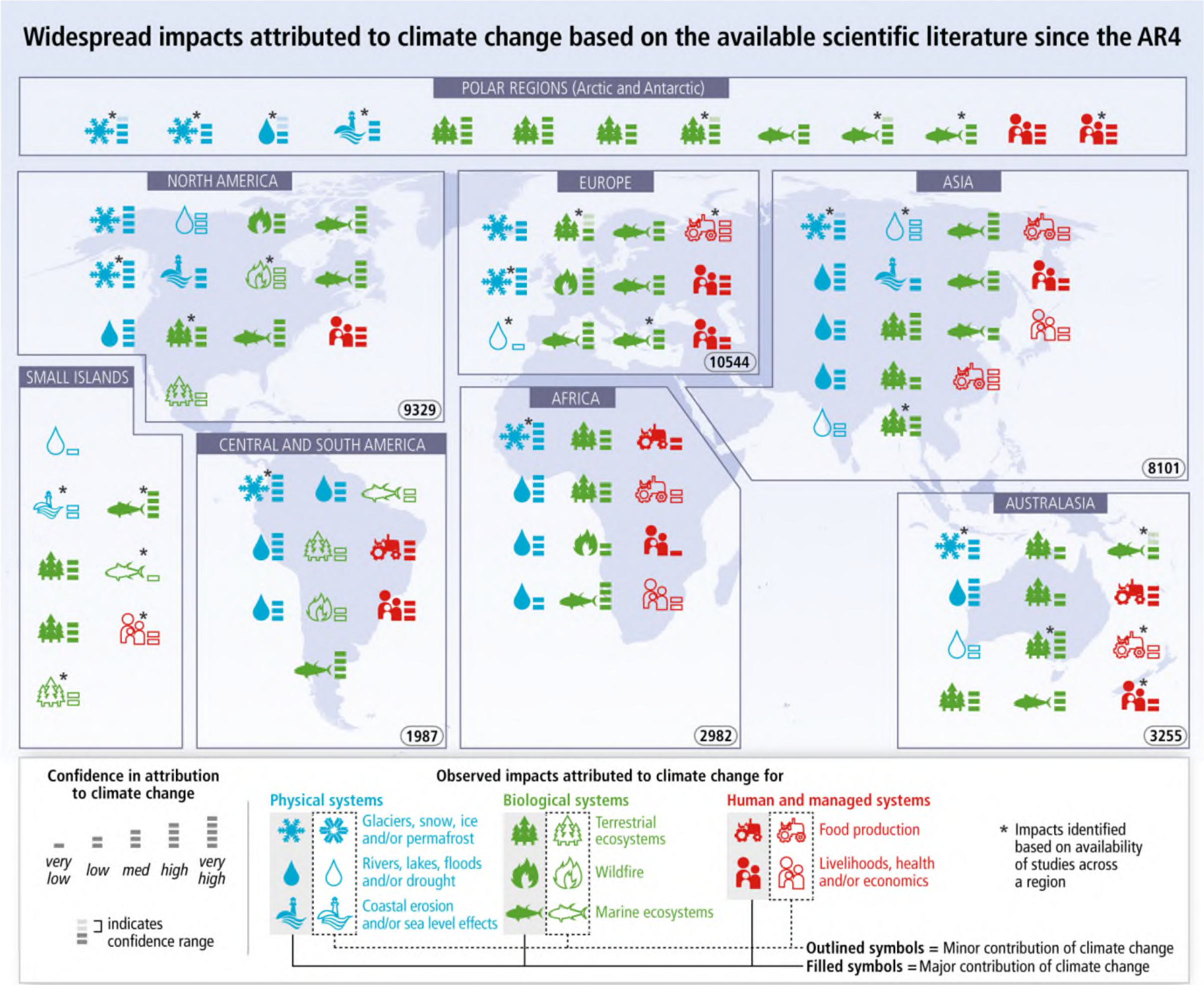

Figure 4 Summary of reported impacts from climate change in the Americas (IPPC 2014, Figure SPM.4)

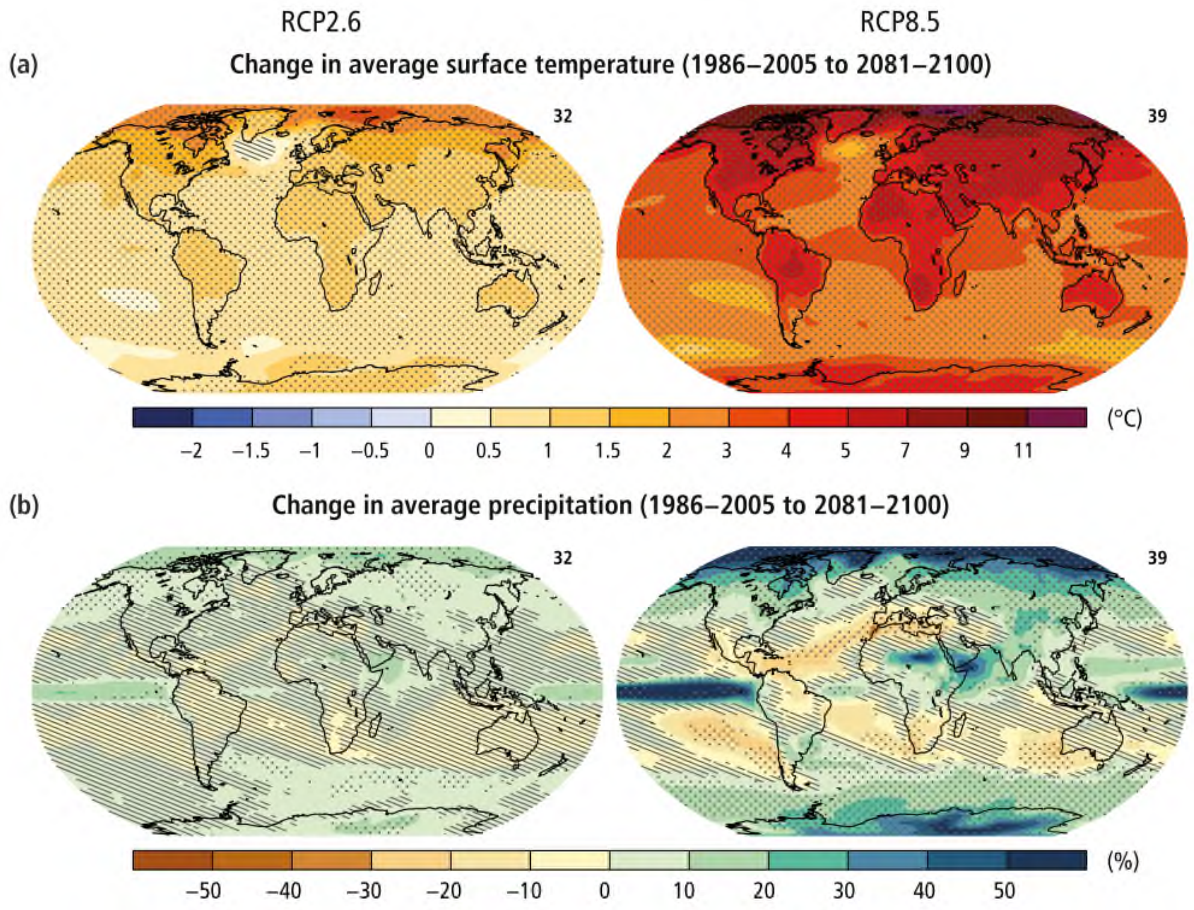

Figure 5 Changes in temperature (a) and precipitation (b) for the periods 1986-2005 to 2081-2100 (IPPC 2014, Figure SPM.7)

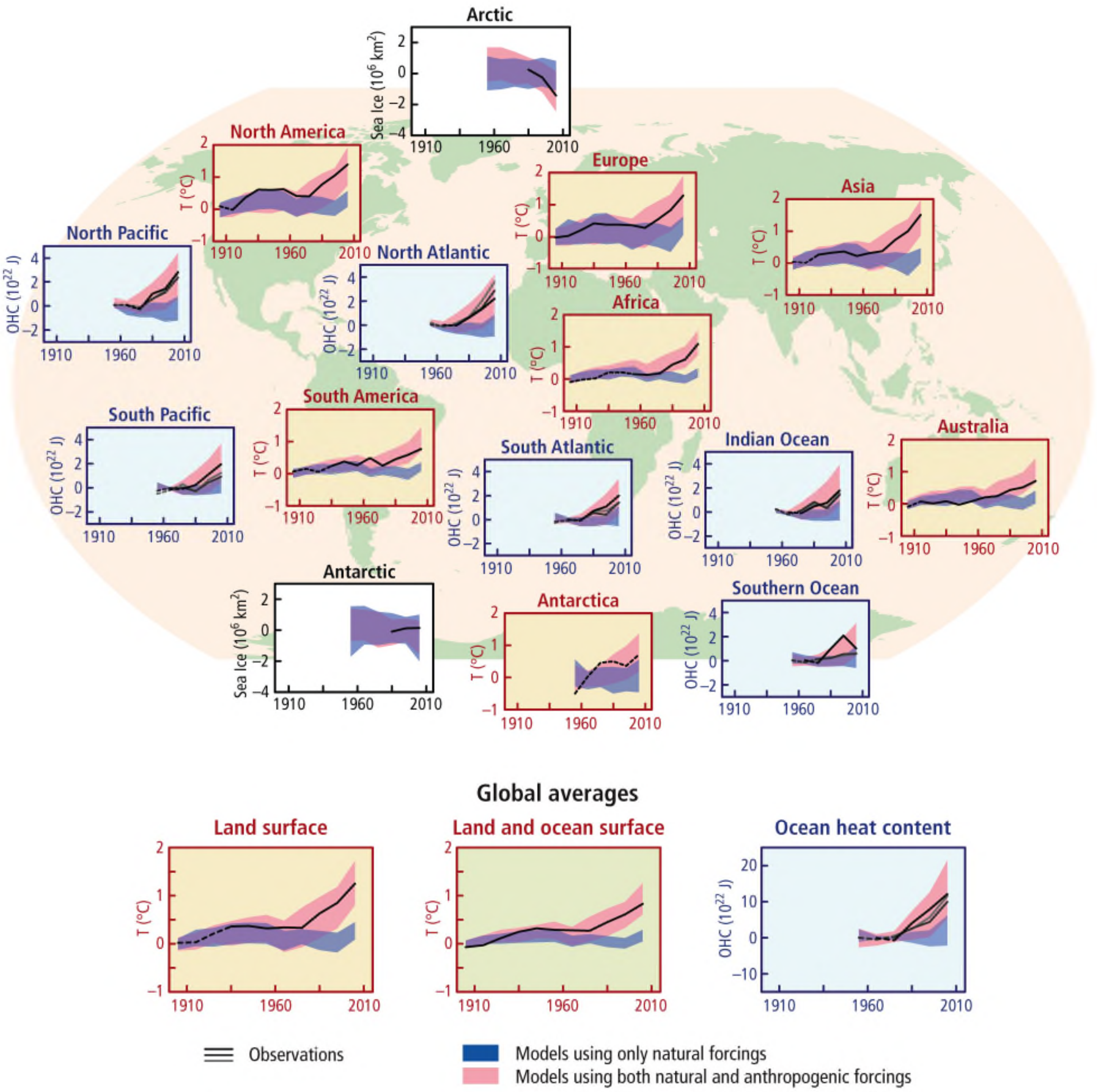

Figure 6 Climate change model results for temperature both including (pink) and excluding (blue) anthropogenic factors compared to measured behaviour (IPPC, 2014, Figure 1.10)

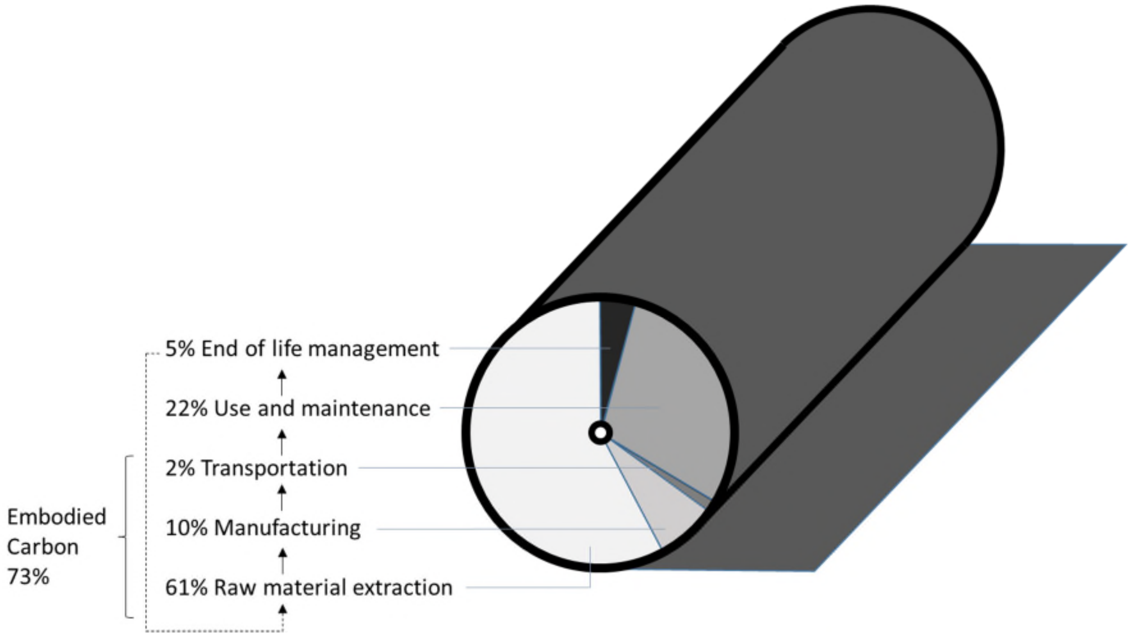

Figure 7 Example of contributions to the EC of a product

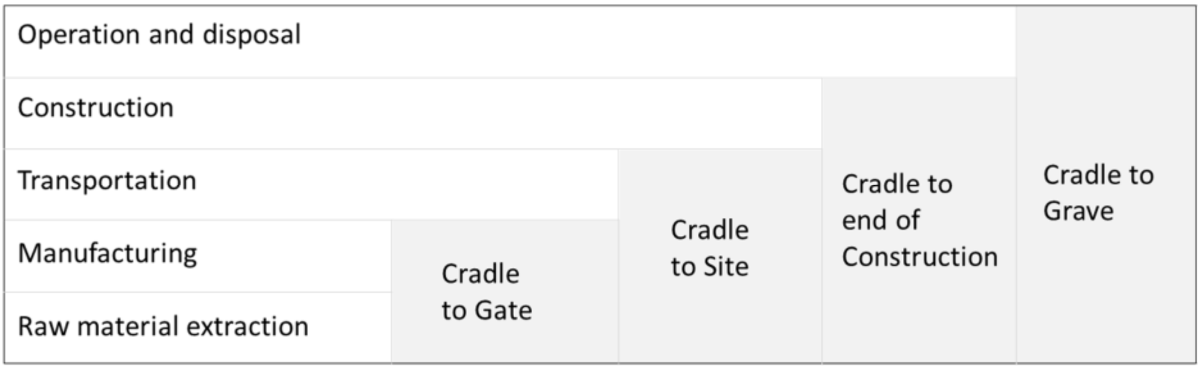

Figure 8 Life Cycle Analysis boundaries for typical stages of product manufacture and application

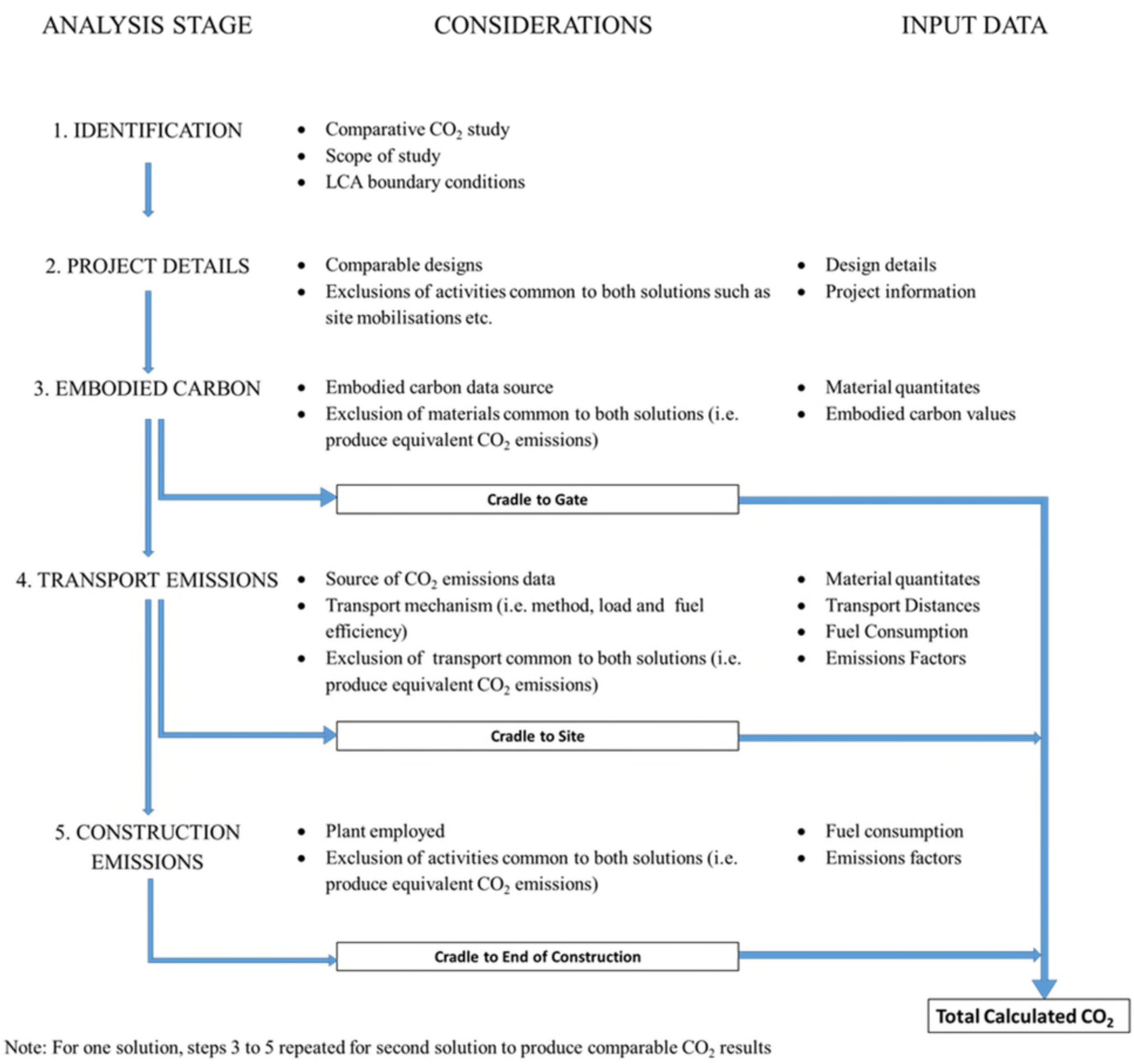

Figure 9 Five stage framework for a CO_2 assessment of a construction solutions (after Dixon *et al.* 2016)

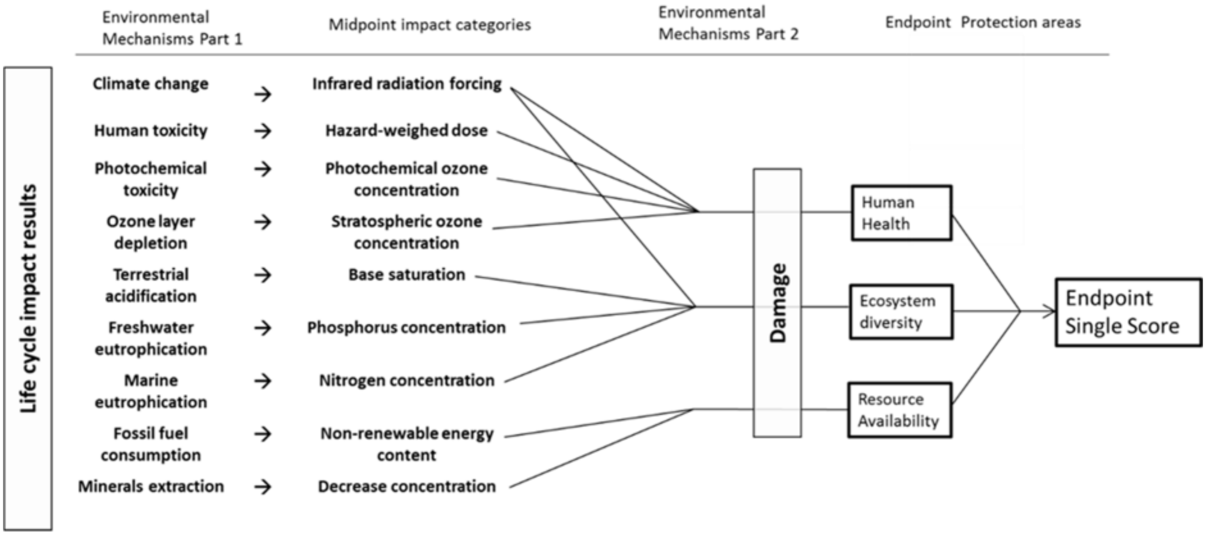

Figure 10 Summary of LCA mid- and end-point indicators employed by Damians *et al.* (2016a)