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1 **Global Challenges, Geosynthetic Solutions and Counting Carbon**

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11

12 **Abstract**

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

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

33 **1 INTRODUCTION**

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

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

53 **2 SUSTAINABLE DEVELOPMENT**

54 The key question faced by the population of the earth is whether sustainable global development is
55 achievable as low and middle income countries strive to improve their standard of living through
56 delivery of infrastructure to provide critical life lines for people (e.g. safe places to live, clean water,
57 food, mobility and energy)? This leads to a secondary question: Does the geosynthetics community
58 have a role to play in delivering sustainable development? It is widely acknowledged that the current
59 model of global development is unsustainable. If low and middle income countries attempt to
60 replicate the approach and forms of infrastructure that have developed in high income countries in
61 the last 200 years, this will lead to exhaustion of natural resources and generation of greenhouse gas
62 (GHG) levels (i.e. of which CO₂ is the most prevalent and along with methane the most important)

63 that will cause irreversible climate change and adverse impacts to populations across the globe.
64 Therefore, in simple terms the global aim is to deliver “development that meets the needs of the
65 present without compromising the ability of future generations to meet their own needs”
66 (Brundtland, 1987). Although a more complete definition uses the principle of *The Three Pillars of*
67 *Sustainability* and for the complete sustainability problem to be solved the three pillars of social,
68 environmental, and economic sustainability must each be sustainable. It should be noted that this
69 paper primarily considers environmental sustainability.

70 **3 USES OF GEOSYNTHETICS**

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

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

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

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

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

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

115 **4 SUSTAINABLE DEVELOPMENT GOALS**

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

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

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

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

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

151 **5 CLIMATE CHANGE**

152 **5.1 Context**

153 Climate change is of overarching concern as it impacts on all of the development goals. Those
154 working to deliver sustainable solutions must do so in the context of the climate change projections
155 as these provide both drivers and a framework within which future infrastructure should be
156 designed and will be operated. Failure to deliver infrastructure that mitigates climate change and/or
157 delivers adaptation solutions, will condemn millions of people to a future quality of life that is not
158 improved, and may even deteriorate, and the goals will not be achieved. The authors have

159 experience using climate change information to investigate the impacts of projected change on
160 critical infrastructure (e.g. Dijkstra *et al.* 2014). This experience investigating and questioning the
161 science behind the headlines reported in the media has enabled a view to be established on both
162 the rigour and usefulness of information currently available. This is shared in this paper as it is of
163 critical importance that designers understand the context of their solutions and the use that can be
164 made of climate change information.

165 **5.2 Climate change trends: Past and future**

166 Although people still debate the causes of climate change and the media continue to report the
167 views of groups who *believe* (Section 5.5) that climate change is not occurring, the most recent
168 Intergovernmental Panel on Climate Change (IPCC) report in 2014, the 5th in the series, presents
169 unequivocal evidence that the climate system is warming (IPCC 2014). Since the 1950s many of the
170 observed changes are unprecedented over decades to millennia and it is very likely that human
171 influence has been the dominant cause of the observed global warming since the mid-20th century.
172 The report concludes that we (the world's population) must reduce future greenhouse gas emissions
173 to better manage the impacts of climate change on the environment, economy and society. As an
174 example of the changes that are already occurring, global temperatures for January to September
175 2016 have been about 0.88°C above the average for the 1961-1990 reference period (World
176 Meteorological Organization, 2016). This is the value averaged over the entire earth's surface
177 including land and oceans and not a site specific measurement. Figure 3 shows annual variation in
178 global average temperatures illustrating the warming trend of the last century (IPCC, 2014, Figure
179 SPM.1). The IPCC (2014) report warns that in the future, continued GHG emissions will cause further
180 warming and changes in all components of the climate. Global surface temperature change for the
181 end of the 21st century is likely to exceed 1.5°C relative to 1850 to 1900 period and contrasts in
182 precipitation between seasons will increase.

183 **5.3 Impacts of climate change**

184 IPCC (2014) present detailed assessments of impacts for all regions of the earth and across a range
185 of sectors that have already been experienced and that can be attributed to climate change. As an
186 example, Figure 4 taken from IPCC (2014) summarises the reported impacts from climate change
187 globally. The evidence is taken from published peer review papers reporting scientific studies. There
188 are already measureable impacts in physical, biological and human/managed systems. In Figure 4,
189 confidence that climate change is the cause is indicated by the height of the column, the colour

190 denotes the type of system and the cartoon the specific impact (e.g. the high confidence in (blue)
191 impact on rivers, lakes, floods/droughts in North and South Americas).

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

198 **5.4 Causes and uncertainty**

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

209 However, despite the clarity and consistency of the climate change projections there is considerable
210 uncertainty due to a number of factors. Firstly, the level of future global GHG emissions is unknown
211 so the projections use a family of four emission scenarios, the likelihood of each being dependent on
212 the success or otherwise of climate change agreements and hence of plans to deliver the sustainable
213 development goals. Although the relative likelihood of emissions scenarios is unknown, climate
214 change is almost independent of emissions scenario in the next few decades (IPPC, 2014) and,
215 therefore, change will still occur even if GHG emissions are drastically cut in the near future, which is
216 highly unlikely. A second important source of uncertainty in projections is due to the natural
217 variability of weather. This natural variability is incorporated in projections by running models with
218 the same emissions but different initial conditions multiple times. Thirdly, is modelling uncertainty
219 that is due to our current incomplete understanding of climate processes and inability to model
220 them perfectly. This is incorporated in projections by aggregating the outputs from many models
221 (e.g. produced by national bodies from around the world responsible for climate change projections

222 and research organisations) and multiple runs. This detailed consideration of uncertainty informs the
223 projections published by IPPC and also those produced by other bodies. For example, the UK climate
224 change projections UKCP09 (Murphy *et al.*, 2009) are presented in a probabilistic framework.

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

229 **5.5 Confidence in climate change projections**

230 IPCC's 5th Assessment Report (2014) provides a comprehensive assessment of the physical science
231 basis of climate change. It comprises 14 chapters, has multiple annexes and supplementary material,
232 800 scientists have contributed to the report and many scientific bodies around the world have
233 reviewed it. In contrast, there is no significant body of evidence to contradict the findings of the
234 report. However, as noted in Section 5.2, there are still vociferous climate change deniers driven by
235 a range of motivations including scientific, theological and political. It should be recognised that the
236 IPCC (2014) conclusions are based on the scientific method: Systematic observation, measurement
237 and experiment, and the formulation, testing and modification of hypotheses.

238 **5.6 Global action on climate change**

239 The 2015 United Nations Framework Convention on Climate Change held in Paris, December 2015
240 (United Nations 2015b), delivered the latest in a series of climate change agreements in which
241 signatory countries agreed to deal with greenhouse gas emissions mitigation, adaptation and finance
242 starting in the year 2020. At this event a global agreement was reached by an unprecedented 196
243 parties (i.e. countries and confederations such as the European Union) on 12th December 2015. The
244 agreement set a goal of limiting global warming to less than 2°C. As of December 2016, 194 parties
245 had signed the treaty, 116 of which have ratified it. By October 2016 there were enough countries
246 that had ratified the agreement for it to enter into force, and it went into effect on 4th November
247 2016. However, given the change in political leadership in the USA in January 2017, who are one of
248 the highest GHG emitters, to an administration that is sceptical about the causes of climate change,
249 there is growing uncertainty around the likely effectiveness of the treaty given that at its core is a
250 requirement to develop, disseminate and adopt practices that deliver sustainable development.

251 Despite acknowledged limitations of the Paris agreement, it is a breakthrough agreement with all
252 major countries initially included. The target of not exceeding 2°C in comparison to pre-industrial
253 level is to be achieved by controlling anthropogenic GHG emissions. A significant aspect of the

254 agreement is that it was made possible because 186 countries published action plans prior to the
255 Paris convention. Each plan sets out the way in which the country intends to reduce their GHG
256 emissions. However, a United Nations (2016b) evaluation of these showed that global warming
257 would still be between 2.7°C and 3°C (i.e. above the critical threshold set by scientists). Therefore,
258 the Paris agreement asks all countries to review these contributions every five years from 2020
259 onwards. One of the main principles of the climate negotiations was that countries have common
260 but differentiated responsibilities when it comes to climate change, in particular depending on their
261 wealth. The agreement establishes an obligation for industrialized countries to provide climate
262 finance for poor countries, while developing countries are invited to contribute on a voluntary basis.

263 **5.7 Actions to make a difference**

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

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

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

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

300 While the scale of the challenge is somewhat daunting, examples exist of how high level global
301 agreements are resulting in local and industry specific change. As part of the Kyoto Protocol (United
302 Nations, 1998) produced following the 1997 Kyoto climate change conference, the European Union
303 (EU) agreed to reduce GHG by 8% below 1990 levels by 2012. Post 2012 the EU adopted a policy to
304 reduce GHG emissions by 20% from 1990 levels by 2020. In the UK, the Climate Change Act (United
305 Kingdom Government, 2008) introduced a legally binding GHG emission reduction target of 80% by
306 2050. How to achieve this target is defined in *The Carbon Plan 2011, delivering a low carbon future*
307 (United Kingdom Government, 2011). While the legislation is broad and no construction specific
308 targets are set, transport, waste and resource efficiency are areas noted as being expected to
309 contribute to meeting the UK targets for GHG emission reduction. There is a focus on zero carbon
310 operation of infrastructure but no mention of savings during the construction phase. However, the
311 UK construction industry has developed a strategy articulated in the report *Construction 2025*
312 (United Kingdom Government, 2013), which identifies low carbon and sustainable construction as a
313 strategic priority of the industry, with an ambition to reduce GHG emission by 50% by 2025. There is
314 an expectation that GHG emission will be a criteria used to select construction solutions and all
315 major projects have to have GHG evaluation as part of their environmental assessment.

316

317 **6 A MEASURE of SUSTAINABILITY: COUNTING CARBON**

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

326 Carbon footprint is a measure of total GHG emissions caused directly and indirectly by a person,
327 organisation, event or product. It is measured in tonnes of carbon dioxide equivalent (tCO₂e). A
328 carbon footprint can cover emissions over the whole life of a product, service or solution (i.e.
329 including a construction solution) and embodied carbon (EC) is an indicator of cumulative carbon
330 emissions used in the solution adopted. Figure 7 shows an example subdivision of a hypothetical
331 material and processes contributing to the EC of an end product, such as a geosynthetic. It should be
332 noted that sometimes Embodied Energy is reported in place of Embodied Carbon. Conversion
333 between the two measures needs knowledge of the CO₂ emitted during generation of the energy
334 used (DEFRA, 2013). This is country specific and hence is a challenging calculation to undertake as
335 information on mixes of energy sources is sparse and this currently makes international comparisons
336 difficult.

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

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

355 **7 EMBODIED CARBON FOR GEOSYNTHETIC MATERIALS**

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

367 **8 LIFE CYCLE ASSESSMENT FOR GEOSYNTHETIC SOLUTIONS**

368 **8.1 Framework and calculation methods for project carbon footprint**

369 To ensure the accuracy and impact of the case studies that compare EC of geosynthetic based and
370 alternative construction solutions requires a consistent and robust CO₂ calculation framework. This
371 ensures the validity and credibility of the results by comparing like for like activities with respect to
372 CO₂ emissions generated. Figure 9 details the framework for a CO₂ assessment of a construction
373 solution incorporating geosynthetics. The framework comprises five stages of analysis, however,
374 depending on the LCA boundaries, Stages 4 and 5 may be omitted.

375 **8.2 Example case studies**

376 There is a growing body of literature detailing studies of the sustainability credentials for
377 geosynthetic based solutions. These invariably use a derivation of the LCA approach introduced in
378 Section 6 and all include comparisons with non-geosynthetic solutions. While all use EC as a measure,

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

392 The UK Waste & Resources Action Programme (WRAP) published a report in 2010. The study details
393 calculation of CO₂ for six case studies for a range of construction activities. LCA boundaries used are
394 Cradle to Gate. IGS UK Members provided information. The case studies showed how the use of
395 geosynthetics amongst other benefits can also reduce the amount of imported fill. This provided CO₂
396 savings from the embodied carbon emissions from quarrying of fresh fill as well as that from the
397 transportation of these materials on and off site. The WRAP (2010) study delivered an accessible
398 report with a very clear unambiguous conclusion that construction solutions incorporating
399 geosynthetics led to significant cost and CO₂ savings. However, a limitation is that all six applications
400 analysed are on reinforcement. Material embodied carbon values are taken from the available
401 version of the ICE database (Hammond and Jones, 2011), including for the geosynthetics. Also, the
402 relationship between embodied energy and embodied carbon for a given material is unclear.

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

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

420 Analysis of EC for a landfill capping project is reported by Raja *et al.* (2014). The study considers a
421 one year capping project for an area of 9572 m² and compares the CO₂ emissions produced by the
422 geosynthetic barrier design used and an alternative clay liner solution. The LCA boundaries are
423 Cradle to End of Construction and the total CO₂ values include: embodied carbon in materials,
424 transport of materials to site and construction process. All EC values for the materials are from the
425 ICE database. The construction element focuses on compaction effort for the regulating layer and
426 clay and considers: type of plant; thickness of layer; number of passes; and total layer thickness. It
427 was noted that the comparison of alternative solutions was sensitive to the EC values used for
428 excavating the clay soil (i.e. demonstrating that the ICE database has inconsistent EC values for
429 materials other than plastics) and the transport distance for the fill. The findings from this study
430 were consistent with others, demonstrating reduced CO₂ for geosynthetic based solutions compared
431 to alternatives.

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

444 cumulative energy demand and considering six midpoint environmental indicator categories, all
445 three endpoint damage categories and in terms of the endpoint single scores.

446 Damians *et al.* (2016b) then extend this study using a full sustainability assessment methodology to
447 select the best option for the same candidate gravity and MSE walls used in Damians *et al.* (2016a).
448 The study employs analyses carried out using the value integrated model for sustainable evaluations
449 (Mives) methodology, which is based on value theory and multi-attribute assumptions. Damians *et al.*
450 (2016a) explain how indicator issues are scored, weighted and aggregated to generate final
451 numerical scores that allow solution options to be ranked. The final scores include an adjustment
452 based on stakeholder preferences for the relative importance of the three sustainability pillars (i.e.
453 environmental, economic and societal/functional). The results reported show that MSE wall
454 solutions were most often the best option in each category compared to conventional gravity and
455 cantilever wall solutions and, thus, most often they were the 'best' solution when scores from each
456 pillar were aggregated to a final score. The methodology used by Damians *et al.* (2016b) for this full
457 sustainability assessment is a powerful tool and will be of interest to those wishing to assess a wider
458 range of geosynthetic solutions than the reinforcement applications considered to date and to
459 consider all three sustainability pillars.

460 Heerten (2012) discusses reduction of climate-damaging gases (i.e. GHG) in geotechnical engineering
461 by use of geosynthetics. This study compliments the results of the WRAP (2010) study. It compares
462 classical construction techniques and geosynthetic construction alternatives and highlights the CO₂
463 savings of employing geosynthetic solutions in steep slope and road applications; however the study
464 was again limited to the function of reinforcement. It considers the cumulated energy demand (CED)
465 and climate related CO₂ emission for products, their transport to the manufacturer and to the site as
466 well as installation. It concludes that a considerably smaller CED and CO₂ emission is shown for the
467 geosynthetic alternatives for the range of applications reviewed.

468 Dixon *et al.* (2016) extend the number of EC studies for non-reinforcement geosynthetic applications
469 employing geotextiles. An additional advance is the use of product specific EC values given by Raja *et al.*
470 (2015) rather than using generic values for plastic from the established data bases detailed in
471 Section 7. Three construction case studies are detailed with EC values calculated for both geotextile
472 based and alternative solutions. Two of the cases consider protection and working platform
473 applications respectively (based on a functional unit 1m² plan area, which is comparable to the
474 approach taken by Stucki *et al.*, 2011) and cradle to site LCA boundary conditions. The influence of
475 haulage distance for mineral components on total EC values is also considered. The third example
476 compares EC for geosynthetic and soil based landfill capping solutions. The LCA boundary of cradle

477 to end of construction is defined and a unit area of 1 ha area is considered to enable EC from
478 construction activities to be meaningfully included. All three case studies demonstrated that
479 solutions employing geosynthetics can result in significant reduction in EC and in addition they
480 highlight the importance of comparing the EC for the whole construction solution and not simply the
481 component products.

482 **8.3 Summary: Counting carbon**

483 Sustainability of materials and processes are commonly assessed by calculating the carbon emissions
484 (CO₂) generated. This is a simplification but the ease of calculation encourages comparisons of
485 solutions, makes outputs of assessments accessible, transparent and repeatable, and CO₂ savings
486 can readily be counted towards industry, national and international targets. A common LCA
487 framework for calculating embodied carbon of construction solutions that incorporate geosynthetics
488 is now well established and there is a growing literature that demonstrates use of the approach and
489 reports examples of assessments that conclude solutions incorporating geosynthetics are
490 consistently more sustainable based on EC, but also using a range of other environmental indicators.
491 Savings in EC are often realised because geosynthetics allow use of site derived often 'marginal' soils,
492 thus reducing the amount of imported fill material; this minimises the transport related carbon
493 emissions. A number of the studies have also concluded that geosynthetic based solutions also
494 delivered significant cost savings. The methods outlined can be used to undertake site specific
495 calculations that inform decisions on selection of construction approaches that contribute to
496 sustainable practice. The need for sustainable construction solutions is a major opportunity for the
497 geosynthetics industry, particularly given the cost savings that can also result.

498 **9 ACHIEVING SUSTAINABILITY DEVELOPMENT GOALS**

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

510 the important role that geosynthetic solutions will play as people and nations adapt to global change,
511 including improved resilience to extremes of weather.

512 United Nations' Sustainable Development Goals challenge nations, organisations and citizens to
513 make a difference to the lives of millions, including: providing access to clean water and sanitation;
514 building and operating resilient infrastructure; and sustainable use of resources. Tackling the
515 impacts of climate change underpins all of the development goals. Equal focus is needed to mitigate
516 future GHG emissions and to develop adaptation solutions to meet impacts of the climate change
517 that is already occurring and is locked into the future, irrespective of reductions in GHG that will
518 result from the Paris agreement. By appropriate use of geosynthetics and considering the doctrine of
519 marginal gains, the challenge for the geosynthetics community is to play a leading role in helping
520 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	<ul style="list-style-type: none"> 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 <i>et al.</i> (2011)/ Functional units	<ul style="list-style-type: none"> 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	<ul style="list-style-type: none"> 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 <i>et al.</i> (2014)/ Projects	<ul style="list-style-type: none"> 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 <i>et al.</i> (2016a)/ Projects	<ul style="list-style-type: none"> 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 <i>et al.</i> (2016)/ Functional units	<ul style="list-style-type: none"> 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 <i>et al.</i> (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.

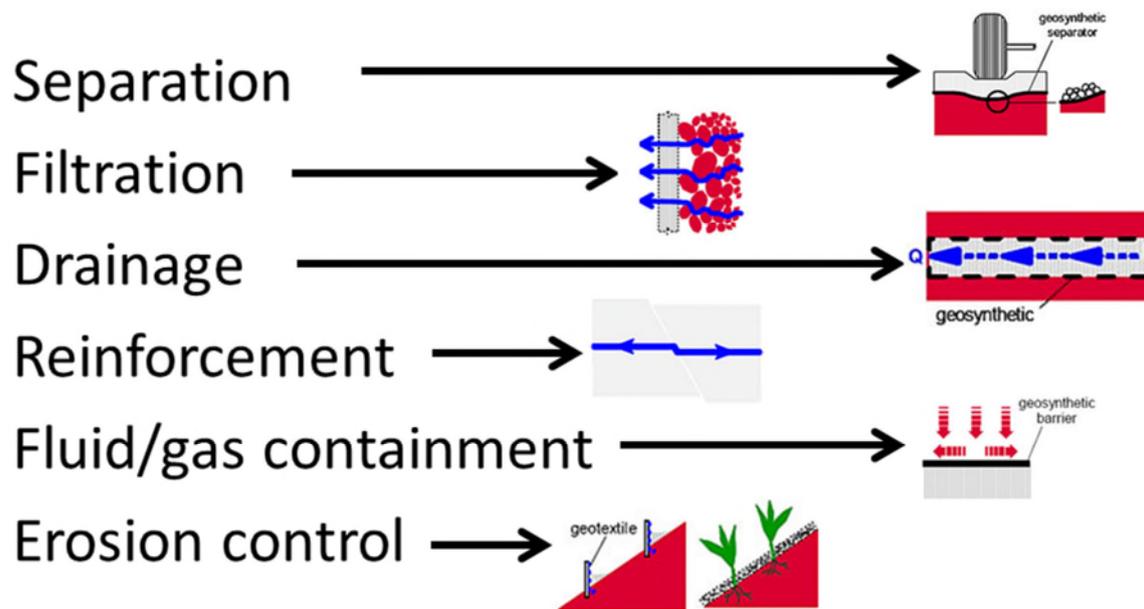


Figure 1 Core functions of geosynthetics



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

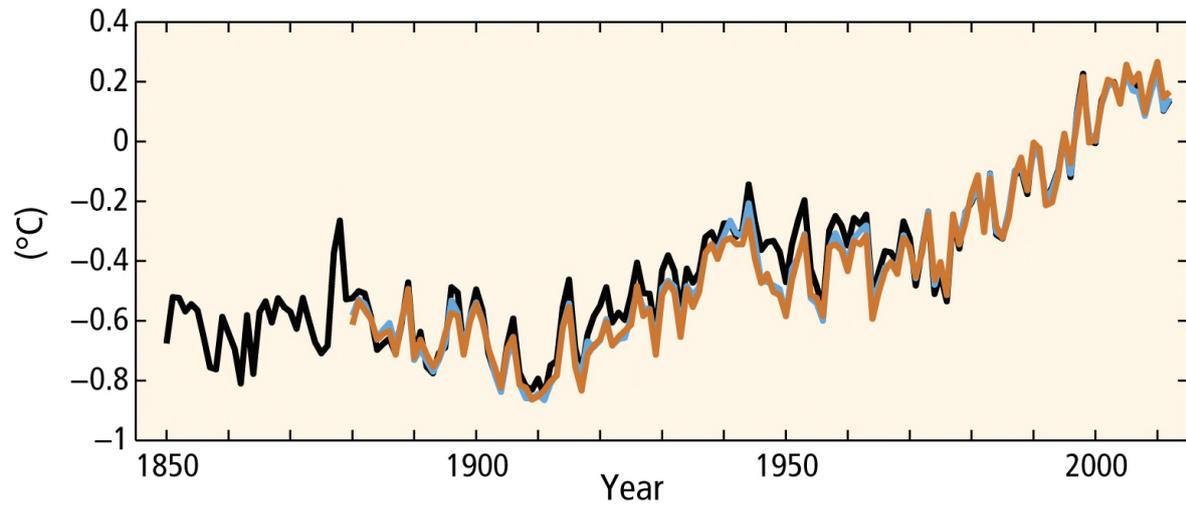


Figure 3 Annual measured variations in global average temperatures illustrating the warming trend of the last century (IPPC, 2014, Figure SPM.1)

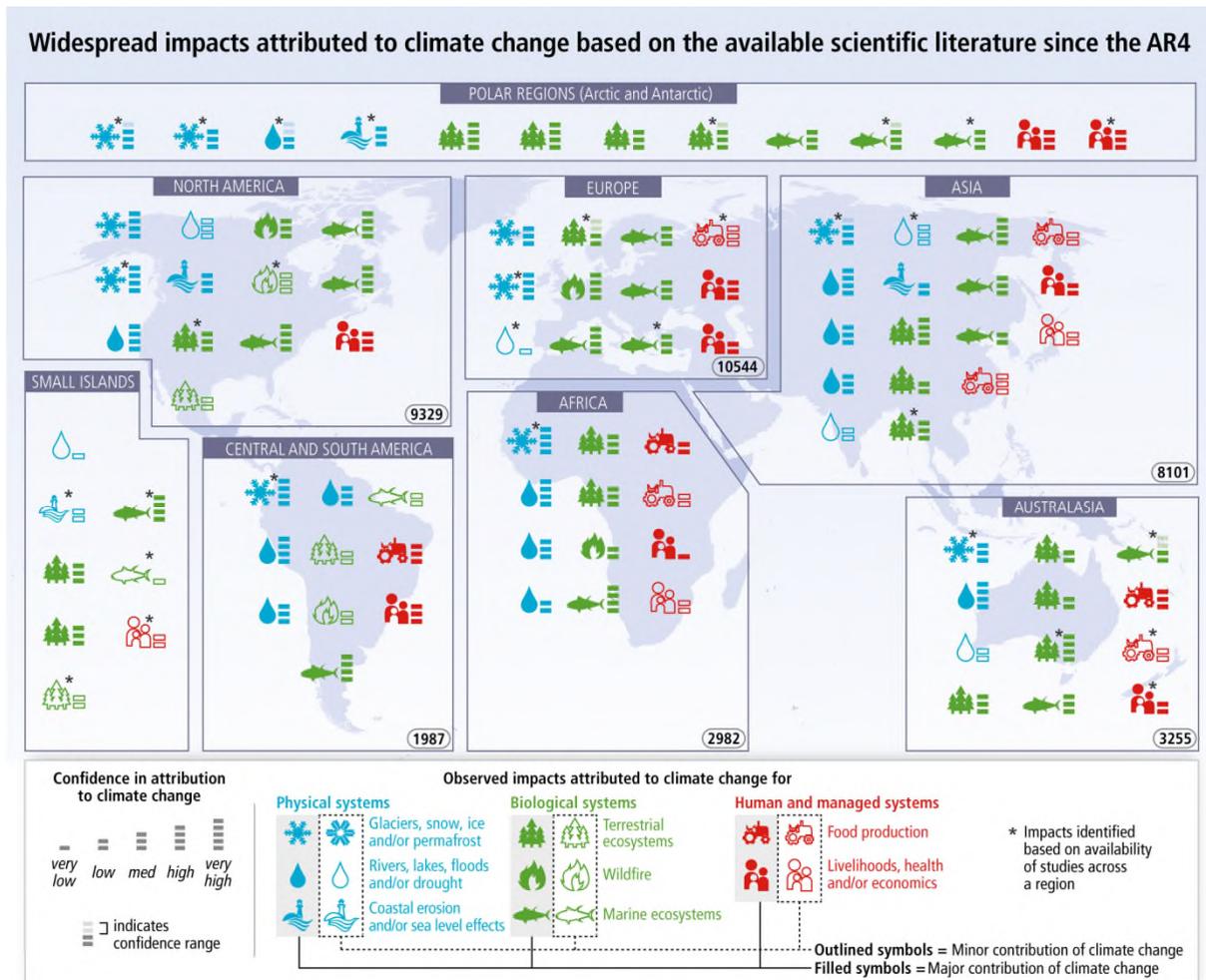


Figure 4 Summary of reported impacts from climate change in the Americas (IPCC 2014, Figure SPM.4)

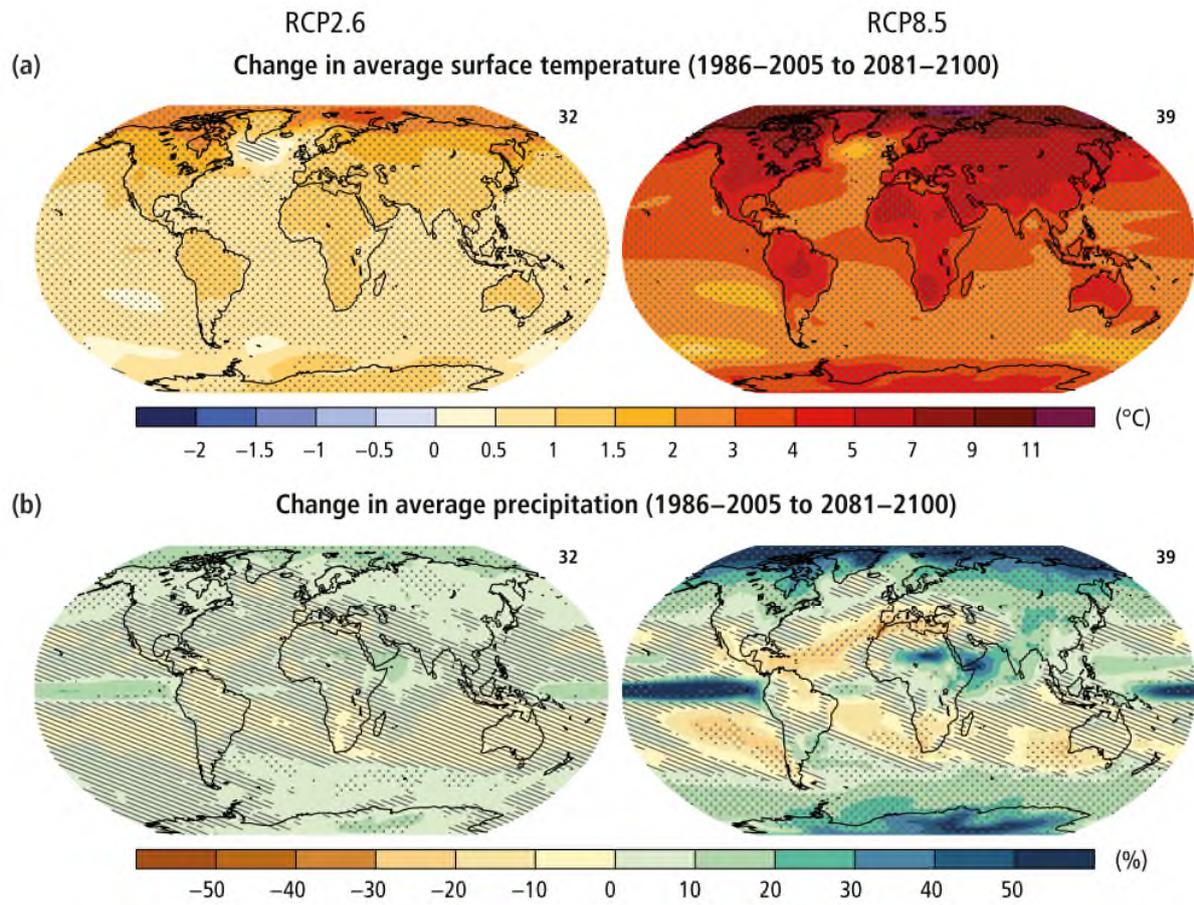


Figure 5 Changes in temperature (a) and precipitation (b) for the periods 1986-2005 to 2081-2100 (IPPC 2014, Figure SPM.7)

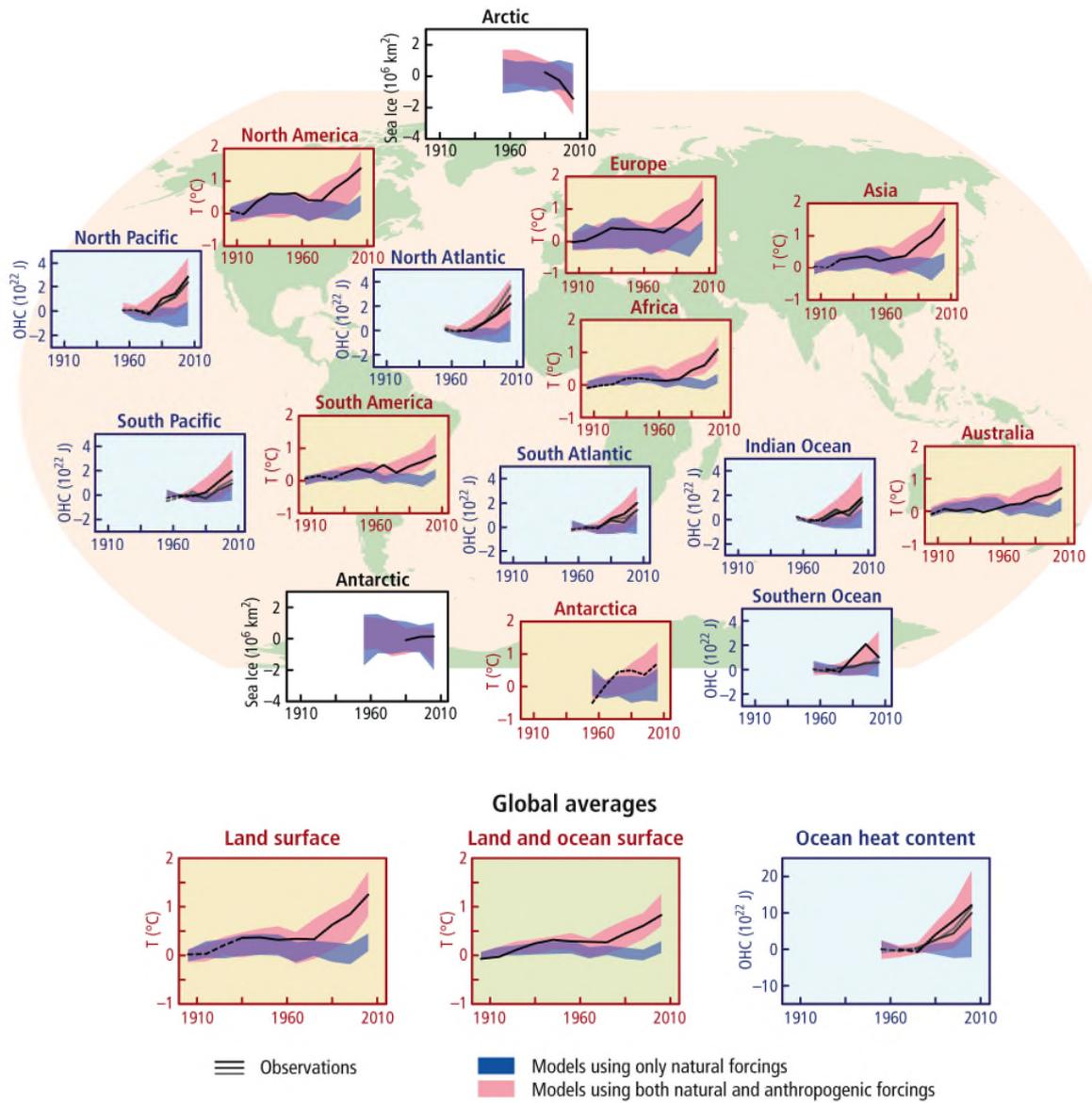


Figure 6 Climate change model results for temperature both including (pink) and excluding (blue) anthropogenic factors compared to measured behaviour (IPCC, 2014, Figure 1.10)

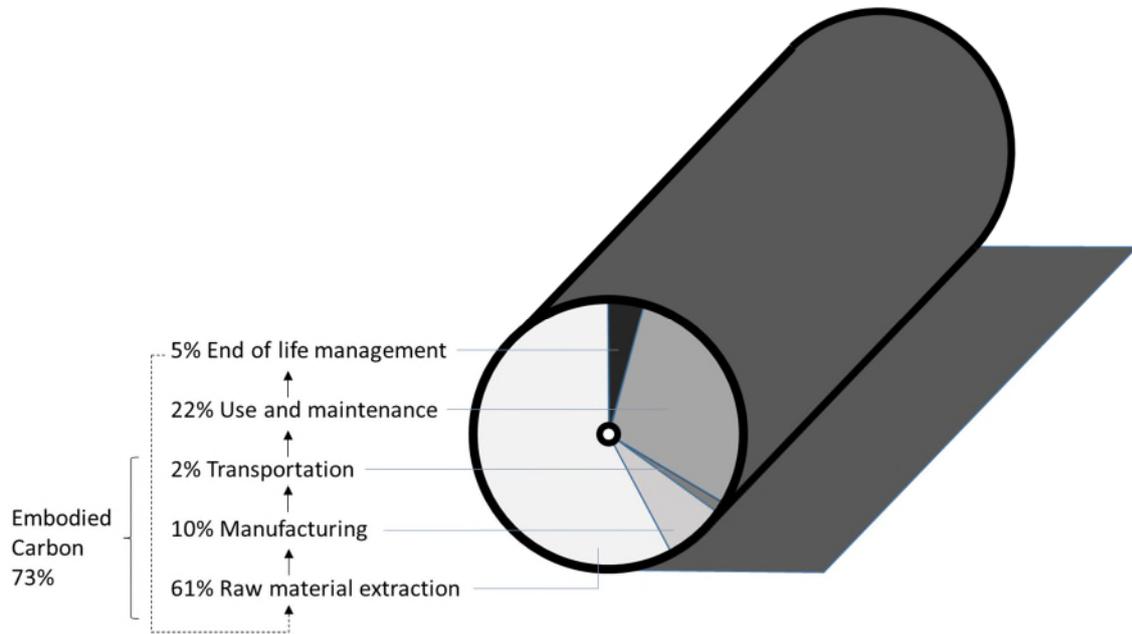
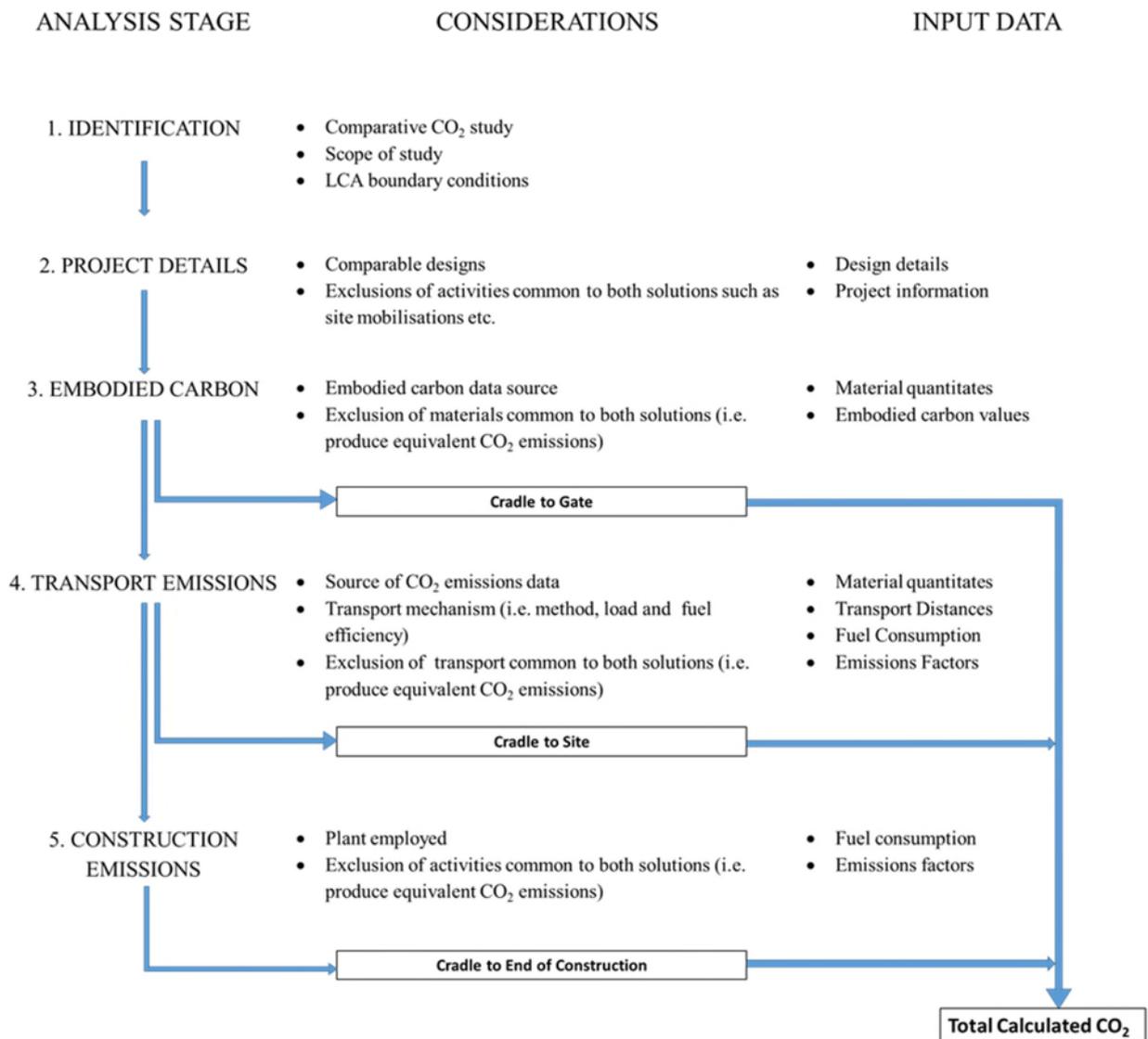


Figure 7 Example of contributions to the EC of a product

Operation and disposal				Cradle to Grave
Construction			Cradle to end of Construction	
Transportation		Cradle to Site		
Manufacturing	Cradle to Gate			
Raw material extraction				

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



Note: For one solution, steps 3 to 5 repeated for second solution to produce comparable CO₂ results

Figure 9 Five stage framework for a CO₂ assessment of a construction solutions (after Dixon *et al.* 2016)

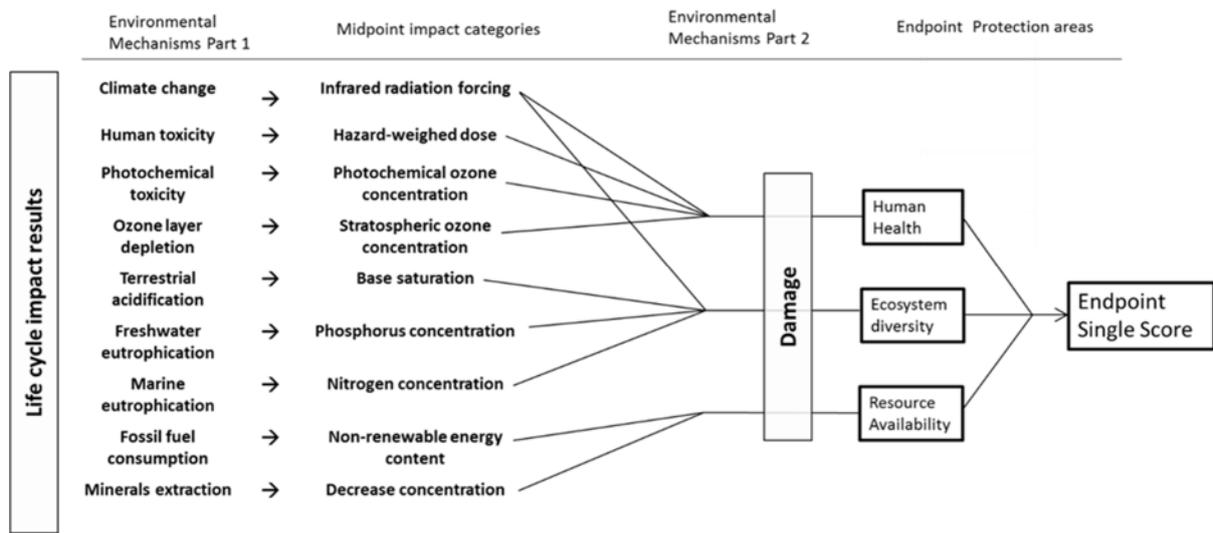


Figure 10 Summary of LCA mid- and end-point indicators employed by Damians *et al.* (2016a)