Assessing the contribution of greenhouse gas emissions towards organisational biodiversity footprints.

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Abstract

Organisations play a key role in addressing climate change and biodiversity loss, which are closely connected. Biodiversity footprinting has initially suggested that greenhouse gas (GHG) emissions may contribute to a large proportion of many organisation's biodiversity impacts. If true, mitigating GHG emissions could help organisations to tackle their climate and biodiversity liabilities in tandem. Consequently, there is a need for greater understanding of (i) how much GHG emissions contribute to biodiversity footprints, across economic sectors (ii) how reliable current footprinting methods are at estimating the impact of GHG emissions. On average, our results estimate that GHG emissions contribute to 47% of an economic sector's total biodiversity footprint. This proportion is much higher than studies into observed biodiversity loss from climate change, which may be due to the methodological limitations of footprinting approaches. Overall, we find that biodiversity footprinting provides a useful but imperfect tool to interrogate the connections between climate change and biodiversity loss in organisations.

Key words:

Climate change; biodiversity loss; Net Zero; Nature Positive; sustainability strategy; footprinting

Introduction

The climate and ecological crises, driven by anthropogenic activities, poses an increasingly large risk for humanity (IPCC, 2023; Pörtner, 2021) and require urgent and systemic action across all sectors of society (Díaz et al., 2019). The private sector has an essential role to play in reducing both biodiversity loss and greenhouse gas (GHG) emissions: e.g. target 15 of the Global Biodiversity Framework explicitly mentions the role of businesses to achieve global goals (CBD, 2022; Leclère et al., 2020; Mace et al., 2018). Climate and biodiversity commitments are therefore taking centre stage within organisational sustainability strategies, including the adoption of Net Zero and, more recently, Nature Positive goals (Hale et al., 2022; zu Ermgassen et al., 2022).

Climate change and biodiversity loss are closely linked and should be addressed in tandem by organisations. Climate change is an increasingly substantial driver of biodiversity loss, driving population declines and extinctions through alteration of habitats, species range shifts, and increasing extreme weather events. It is predicted to overtake land-use conversion as the largest driver of biodiversity loss by the middle of the century (Pigot et al., 2023; Trisos et al., 2019; Newbold et al., 2020; IPCC, 2023; Urban et al., 2016). Mitigating GHG emissions is therefore essential to prevent both current and future biodiversity loss. Similarly, actions to halt and reverse biodiversity loss often support climate change mitigation and adaptation efforts (Díaz et al., 2019; Shin et al., 2022). In recent years there have been a number of calls to integrate climate and biodiversity action across science, policy, and the private sector (Essl et al., 2018; Pettorelli et al., 2021; Pörtner, 2021). The Global Biodiversity Framework explicitly includes a target to minimize the impacts of climate change on biodiversity (2030 Target 8) (CBD, 2022).

Organisational strategies which address drivers of climate change and biodiversity loss concurrently may be more likely to achieve climate and biodiversity goals (Maddinson et al., 2025). Enacting joint climate and biodiversity strategies may also reduce the transition, regulatory and physical risks of inaction for organisations (for example, the risk of ecosystem service disruption caused by climate change-driven weather extremes) (White et al., 2024). Despite this, climate and biodiversity goals have so far largely been considered separately by organisations, highlighted by calls to improve the knowledge-gap on this area (Anthesis, 2025; UNEP, 2024).

At an organisational level, biodiversity footprinting has increasingly been employed to identify the contribution of GHG emissions towards biodiversity loss. Biodiversity footprinting enables

73 organisations to identify, monitor and communicate their largest sources of biodiversity impact
74 across complex value chains and between different actors (Bromwich et al., 2025; Damiani et
75 al., 2023;(Marques et al., 2017). Footprinting methods quantify the contribution of several key
76 drivers of biodiversity loss, such as climate change, land use change, and pollution (IPBES,
77 2019), towards an overall measure of biodiversity impact, termed 'footprint' (Hoekstra &
78 Wiedmann, 2014). Results often suggest a major contribution from climate change to
79 biodiversity loss, with several studies identifying GHG emissions as one of the largest
80 contributors to an organisation's biodiversity footprint (Bull et al., 2022; El Geneidy et al., 2026;
81 Maddinson et al., 2025; Martínez-Ramón et al., 2025). If GHG emissions genuinely do drive a
82 large proportion of organisational biodiversity impacts, then considerable potential exists for
83 achieving climate and biodiversity goals in tandem (Maddinson et al., 2025). Where such
84 cases are identified, sustainability strategies should prioritise mitigation of GHG emissions.
85 Integrated climate and biodiversity assessment may further inform corporate performance
86 measurement; climate and biodiversity risk assessment; and sustainability reporting and
87 disclosure frameworks. Doing so will facilitate more effective action for climate and biodiversity
88 and follows the guidance of frameworks such as the Task Force for Nature-Related Financial
89 Disclosures (Kedward et al., 2023; TNFD, 2025).

90

91 Greater confidence is now needed in the degree to which GHG emissions do drive
92 organisational biodiversity impacts in order to integrate climate and biodiversity strategies.
93 However, concerns remain about the robustness of biodiversity footprinting methods in
94 quantifying biodiversity loss and designing sustainability strategies. Biodiversity footprinting
95 tools are increasingly used by organisations for strategy design, and it is imperative that
96 uncertainties are acknowledged and addressed (Bromwich et al., 2025; Barahmand &
97 Eikeland, 2022; Martínez-Ramón et al., 2025). Further attention must therefore be given to
98 how the biodiversity impacts of GHG emissions are estimated in biodiversity footprinting tools,
99 particularly because uncertainties exist in assessing the effect of future climate change on
100 biodiversity (Dan Li et al., 2022; Iordan et al., 2023). Although climate change is often one of
101 the largest drivers of biodiversity loss in footprinting studies (e.g. (Bull et al., 2022; El Geneidy
102 et al., 2023; Maddinson et al., 2025; Martínez-Ramón et al., 2025)), this trend is not echoed
103 in reviews of biodiversity loss, which highlight land (and sea) use change and direct
104 exploitation of natural resources as the largest drivers (Jaureguiberry et al., 2022; Maxwell et
105 al., 2016). The discrepancy between footprinting studies and other forms of biodiversity
106 assessment warrants further attention to avoid ineffective strategy design, or overemphasis of
107 the impacts of climate change on biodiversity (Caro et al., 2022).

108

109 We evaluate the connection between GHG emissions and biodiversity footprints through two
110 questions. First, we determine how much GHG emissions contribute to biodiversity footprints,
111 across economic sector. We therefore comment on how widespread the opportunities are to
112 mitigate climate and biodiversity impacts together. To do so, we quantify the estimated share
113 of biodiversity footprints driven by GHG emissions across key industrial sectors in the global
114 economy, across a range of footprinting approaches. Secondly, we explore the reliability of
115 footprinting assessments to quantify the impact of GHG emissions, providing a conceptual
116 development for the results generated from the first research question. We compare several
117 footprinting approaches to illustrate how and why footprinting method choices drive different
118 outcomes, as well as the key uncertainties and assumptions of the selected approaches. We
119 further comment upon the discrepancies between footprinting results and other biodiversity
120 studies, which may incentivise different sustainability actions.

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122

123 ## 2. Methods

124 **2.1. Quantifying the contribution of GHG emissions to total biodiversity footprints**

125

126 We used Life Cycle Impact Assessment (LCIA) approaches to quantify our biodiversity
127 footprints in this study. LCIA is a leading approach to quantify biodiversity loss caused by
128 environmental impactful activities across complex value chains and different actors (Bromwich
129 et al., 2024; Bull et al., 2022; Peura, Sami El Geneidy, et al., 2023). LCIA tools build upon the
130 classic life cycle assessment (LCA) methodology, combining LCA outputs for the major drivers
131 of biodiversity loss with characterisation factors (biodiversity impact per unit of environmental
132 driver). LCIA methods are highlighted as potential tools in key sustainability frameworks such
133 as the Taskforce for Nature-relate Financial Disclosures (TNFD) and the EU Corporate
134 Sustainability Reporting Directive (European Commission, 2023; TFND, 2023).

135

136 Methodological or data differences in the most commonly applied LCIA approaches may result
137 in differing results for organisational biodiversity impacts and differing corporate strategies
138 (Bromwich et al., 2025). Our analysis used four different LCIA approaches, namely LC-
139 IMPACT, GLOBIO, IMPACT WORLD + and ReCiPe (Bulle et al., 2019; Huijbregts et al., 2016;
140 PBL, 2019; Verones, 2021). In all four approaches we used global average characterisation
141 factors, which are used to quantify the relationship between GHG emissions and globally
142 distributed biodiversity loss. Regional specific characterisation factors were further used for
143 one approach (LC-IMPACT) based on previous footprinting assessments undertaken by (El

144   Geneidy, 2023). In doing so, we assessed how the inclusion of spatially specific
145   characterisation factors influences our footprinting results.

146

147   To estimate total biodiversity footprints for different sectors of the world economy, we first
148   paired the chosen LCIA approaches with data from the environmentally extended multi
149   regional input-output (EEMRIO) database EXIOBASE. EEMRIO databases are frequently
150   used alongside LCA approaches to estimate biodiversity impacts at an economy level (Bjelle
151   et al., 2021; Marques et al., 2019; Wilting et al., 2021). EXIOBASE provides estimates of the
152   environmental impacts of different product and industry groups (land use and GHG emissions,
153   for example) per unit of consumption (€). We used values from EXIOBASE version 3.8.2
154   (Stadler et al., 2018, 2021), exported to Excel using the python tool pymrio. EXIOBASE values
155   are reported for 200 products and 49 regions (44 countries and five rest of world regions), as
156   well as 21 industrial sectors. To aggregate results according to major sectors, we harmonised
157   EXIOBASE product categories with the NACE classification for European economic activities
158   (eurostat, 2008). We have not considered the implications of EEMRIO choice (EXIOBASE)
159   here, although other databases exist such as Eora and WIOD (Lenzen et al., 2012; Timmer et
160   al., 2014). Previous studies have shown that discrepancies in EEMRIO data sources result in
161   different carbon footprinting values; we would expect similar outcomes for biodiversity
162   footprinting (Moran et al., 2014).

163

164   Next, we calculated the biodiversity footprint intensity (biodiversity footprint per million euros
165   of financial spend) of each biodiversity loss driver, for each sector. We combined EXIOBASE
166   consumption data and LCIA characterisation factors together. For example, the
167   characterisation factor for water consumption (PDF.year/m^3) in LC-IMPACT was multiplied
168   with the consumption value (m^3/Million €) for water consumption from EXIOBASE.
169   Characterisation factors were sourced from the LCIA databases themselves when available,
170   using average factors and a time horizon of 100 years (Verones et al., 2020; Bulle et al., 2019;
171   Huijbregts et al., 2016). When databases were not readily available (as was the case
172   GLOBIO), we used values from previous approaches to collect and harmonise
173   characterisation factors (Sanyé-Mengual et al., 2022). Absolute biodiversity impacts were
174   calculated by multiplying biodiversity impact per million euros of financial spend with values of
175   total financial output per sector. The proportion of impacts driven by GHG emissions was
176   calculated as total impacts due to GHG emissions, divided by total biodiversity impacts
177   summed across ecosystems and drivers. Here, we report biodiversity impacts summed across
178   terrestrial, marine, and freshwater ecosystems without the inclusion of species weights
179   (correcting for different species numbers across ecosystems) (El Geneidy et al., 2023). Our
180   reporting of ecosystem totals is based on common convention for biodiversity footprint results;

181 future studies, however, are needed to see how the inclusion of species weighting results in
182 differing footprinting outcomes.
183
184 Overall, we quantified the contribution of GHG emissions towards total biodiversity footprints
185 of 21 industrial sectors of the global economy, with individual data points available per region
186 and product as provided by EXIOBASE. The full range of data, per LCA approach, industrial
187 sector, region, product, and impact driver, is provided within the Supplementary (SM2). We
188 applied statistical tests to investigate whether the proportion of biodiversity impacts driven by
189 GHG emissions varies according to economic sector and LCIA method choice. We fitted
190 separate multiple linear regression models using the R *stats* package, using proportion of
191 impacts driven by GHG emissions as the dependent variable and economic sector and LCIA
192 method choice respectively as categorical independent variables. Here, we report the extent
193 to which each factor explains variation in the contribution of GHG emissions to biodiversity
194 footprints, reported as R^2 values. Model assumptions of linearity, constant variance
195 (homoscedasticity), normality and independence were verified through residual analysis. We
196 further carried out Spearman's rank correlation tests and coefficients of variation (CV) for
197 economic sector and LCIA method choice data.
198

199 ## 2.2. Evaluating the robustness of GHG emission pathways in
200 ## biodiversity footprinting tools
201

202 To contextualise the results generated in part (2.2.), we explored the robustness of GHG
203 emission pathways across different biodiversity footprinting tools. In doing so, we highlight the
204 assumptions and uncertainties associated with the above results (2.2), as well as the
205 limitations of biodiversity footprint assessments for integrating climate and nature goals. We
206 evaluated the underlying calculation methodologies of a range of LCIA footprinting tools.
207 Approaches were selected from a review by (Damiani et al., 2023), as well as two follow-up
208 papers produced by the same authors since the original publication (Damiani et al., 2023)
209 (identified in December 2024). A total of eight approaches were identified: six out of twenty-
210 three original approaches from (Damiani et al., 2023) and two follow up papers (Iordan et al.,
211 2023; Sif de Visser et al., 2023) (see SM1 for a complete list of approaches). Approaches
212 were selected for analysis due to their widespread utility in organisational footprinting; the
213 availability of open-source online documentation for the approaches; being LCA-based; and
214 not utilising the same methods as other LCIA approaches. Screening of approaches was
215 undertaken based on guidance from expert LCIA practitioners; further detail on the selected
216 approaches is available in SM1. The most recent papers (Iordan et al., 2023; Sif de Visser et
217 al., 2023) are used in the new Global Guidance for LCIA Indicators and Methods approach

218 (GLAM) (Askham et al., 2025). Selected approaches therefore reflect current and developing
219 calculation approaches for the biodiversity impact of GHG emissions.
220
221 To explore the robustness of GHG emission pathways we evaluated the methodology behind
222 each biodiversity footprinting approach. We produced a table outlining the key methodological
223 steps for each approach, including the underlying papers used to determine values of
224 biodiversity impact and assumptions made.
225

3. Results

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3.1. How much do GHG emissions contribute to biodiversity footprints?

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231
232 According to sector-level results, GHG emissions consistently contribute a towards large – but
233 highly variable – proportion of overall biodiversity footprints, across economic sectors (Figure
234 1). On average, our selected footprinting methodologies estimated that GHG emissions
235 contribute to 47% of an economic sector's total biodiversity footprint (SD= 28%). Our results
236 suggest there are many opportunities to achieve climate and biodiversity goals
237 simultaneously, as mitigating GHG emissions may significantly reducing biodiversity
238 footprints. Though our results are somewhat consistent with previous LCIA analyses, they
239 diverge from previous estimates of climate-change driven biodiversity loss obtained via other
240 methodological routes, which place GHG emissions as a much smaller driver of biodiversity
241 impact (compared to land use or direct exploitation, for instance) (e.g. (Caro et al., 2022;
242 Jaureguiberry et al., 2022; Maxwell et al., 2016). There is a concern, therefore, that our results
243 represent an over-estimation of the role of GHG emissions in driving biodiversity loss. The
244 discrepancy between our results and alternative biodiversity assessments is commented upon
245 in depth in the Discussion.
246
247 Our results further indicate that economic sectors may have differing contributions of GHG
248 emissions to biodiversity footprints, therefore driving different strategic priorities. Regression
249 analysis showed that economic sector was a significant predictor for the proportion of
250 biodiversity footprints driven by GHG emissions (Figure 1), explaining around 57% of total
251 variance in impacts (multiple linear model R^2 = 0.57, p = 5.8e-08). Sectors including mining
252 and quarrying (sector B in Figure 1, mean = 64%, SD = 27%) and electricity, gas, steam and
253 air conditioning supply (sector D in Figure 1, mean = 64%, SD = 27%), for example, displayed
254 a high proportion of their estimated biodiversity footprints being driven by GHG emissions. For
255 these sectors, taking actions to reduce GHG emissions may go a long way towards reducing

overall biodiversity footprints. Conversely, sectors such as agriculture, forestry and fishing (sector A in Figure 1, mean = 22%, SD = 23%) and accommodation and food service activities (sector I in Figure 1, mean = 24%, SD = 14%) displayed relatively low contributions of GHG emissions to the overall biodiversity footprint. Here, designing sustainability strategies which are inclusive of climate and biodiversity will likely require large investment in tackling alternative drivers of biodiversity loss (land use and water pollution, for example). Such trends may be used to design sustainability strategies in the absence of extensive biodiversity footprinting data. However, as highlighted in Figure 1, variability within sector results high (standard deviation (SD) = 28%, coefficient of variation (CV) = 56%, all footprinting approaches), indicating the need for more granular information (on-site biodiversity assessments, or product-level data, for instance).
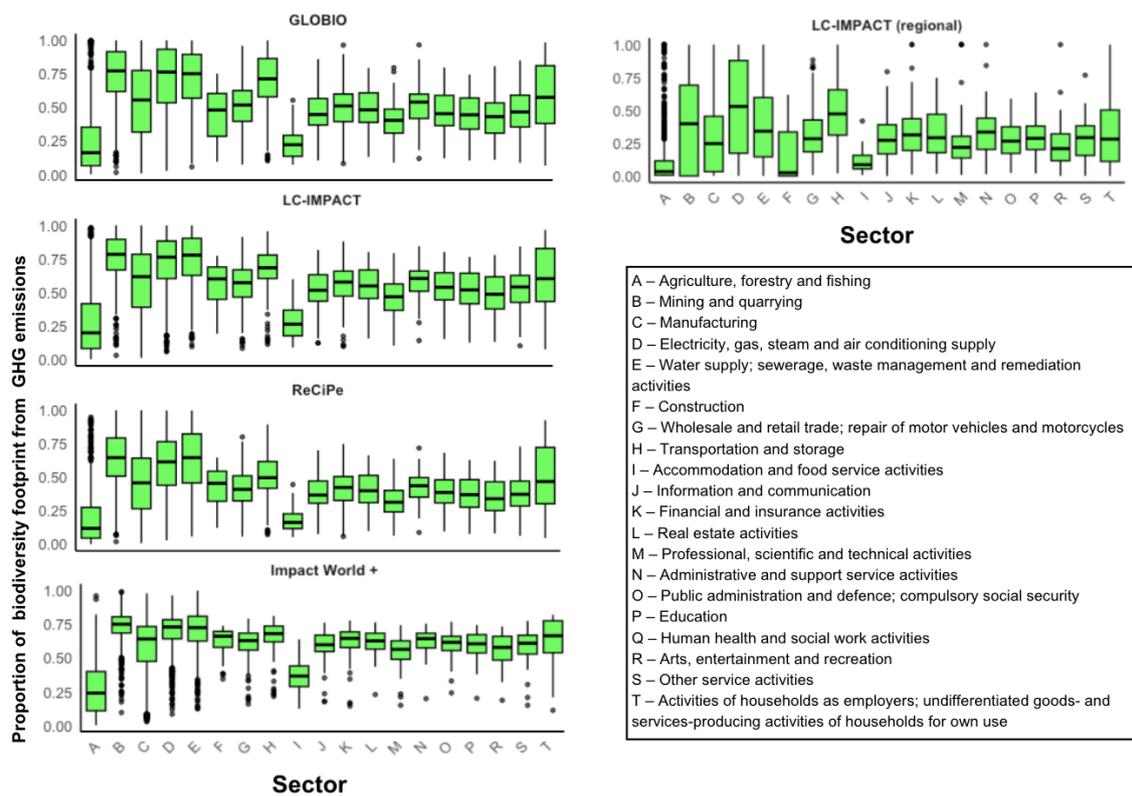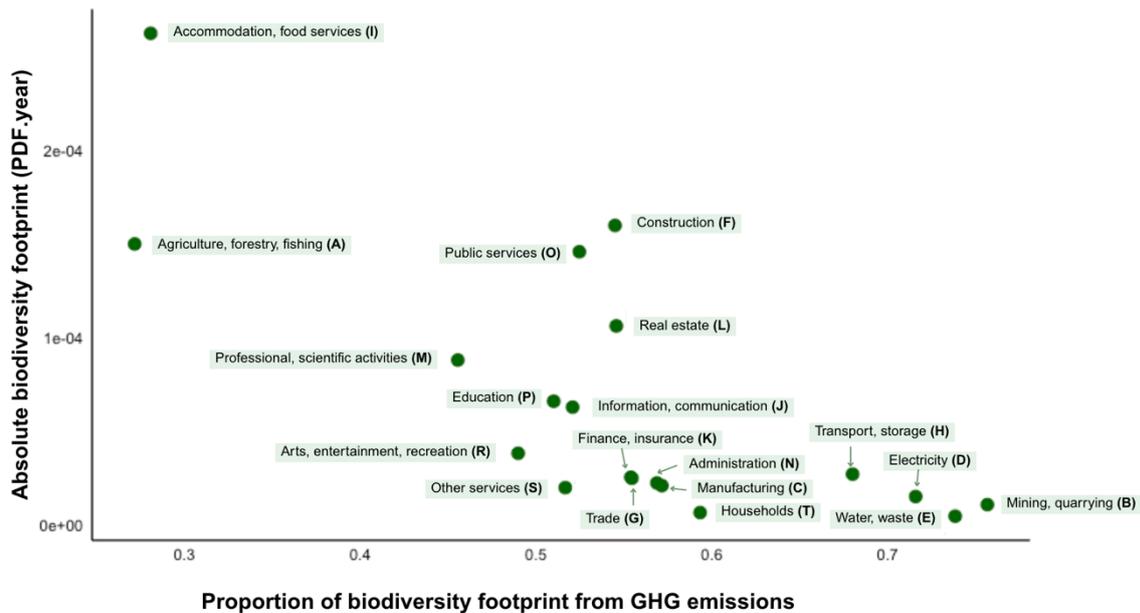

Figure 1: *Proportion of total biodiversity footprint driven by GHG emissions for major sectors of the global economy, based on LCIA footprinting methods GLOBIO, LC-IMPACT, ReCiPe and Impact World +. Results are based on global average characterisation factors for all LCIA approaches except LC-IMPACT ('regional'), which uses region-specific characterisation factors. Horizontal lines in the coloured boxes represent median values; coloured boxes denote interquartile ranges (IQR); whiskers represent range of values within 1.5x the IQR; dots represent outliers beyond 1.5x the IQR.*

277

278   Figure 2 highlights the difference in absolute biodiversity footprint for major sectors of the
279   global economy, and their relation to GHG emissions. Results are reported using LC-IMPACT,
280   with results from the remaining four approaches detailed in the Supplementary (SM3). In
281   Figure 2, we can identify (a) the absolute size of a sector's biodiversity footprint (and therefore
282   how high a priority impact mitigation is) and (b) the proportion of impacts driven by GHG
283   emissions (with high proportions, mitigation of GHG emissions has the potential to significantly
284   reduce absolute biodiversity footprints). Accommodation and food service activities (Sector I
285   in Figure 2), for example, drive a large average absolute biodiversity footprint of 2.6 x 10e -4
286   PDF.year (LC-IMPACT), of which only 28% is caused by GHG emissions. For such sectors,
287   extensive biodiversity strategies outside of their climate neutrality approaches may be
288   required. In comparison, activities with high relative impact of GHG emissions, but low
289   absolute biodiversity footprints may not warrant top priority within an organisation's
290   biodiversity strategy. Water supply, sewerage, waste management and remediation activities
291   (E in Figure 2), for example, drive average absolute biodiversity impacts of 4.8 x 10 e-6
292   PDF.year (LC-IMPACT), 74% of which is estimated to be caused by GHG emissions.
293   Importantly, absolute biodiversity impacts are driven not only by biodiversity impact intensity
294   (biodiversity impact per unit of financial spend) but also the total financial spend of a sector.
295   As such, our results encompass a wide range of spending levels, and drive some unexpected
296   results. Public services, for example has a high biodiversity footprint intensity due to the
297   significant levels of public spending by government (Figure 2, Sector O); in comparison, Mining
298   an Quarrying (Figure 2, Sector B) has an unexpectedly low absolute footprint. A higher level
299   of granularity may be needed to design strategies for individual organisations.

300

301

Figure 2: *Average absolute biodiversity footprint, compared to the proportion of biodiversity footprint driven by GHG emissions. Figures are reported for major sectors of the global economy using the LCIA framework LC-IMPACT. A full list of EXIOBASE names for each sector can be found in Figure (1).*

The large contribution of GHG emissions to biodiversity footprints was seen consistently across LCIA approaches (47% average contribution). We carried out Spearman Rank correlation analyses to compare the average proportion of biodiversity footprint driven by GHG emissions for all EXIOBASE sectors, across footprinting approaches. Our results displayed close alignment between all footprinting approaches (Spearman's r > 0.77) (Figure 3), indicating high levels of similarity between LCIA approaches. The generally high alignment between footprinting results was somewhat surprising, particularly given the diverse number of drivers considered in each LCIA approach (2 to 13 drivers). Regression analysis showed that number of drivers in each LCIA approach was not a significant predictor for the proportion of biodiversity footprints driven by GHG emissions (linear model, β = 0.0072, *p* = 0.12, multiple R^2 = 0.025, n=96). We would expect the proportion of biodiversity footprint driven by climate change to decrease as more drivers (land use change, for example) are included in the calculations. Our results highlight the dominance of GHG emissions within LCIA-based biodiversity footprints, as well as high levels of agreement found between footprinting results. We comment upon these findings in detail- including whether the high level of agreement reflects robustness or shared systemic biases- in the Discussion.
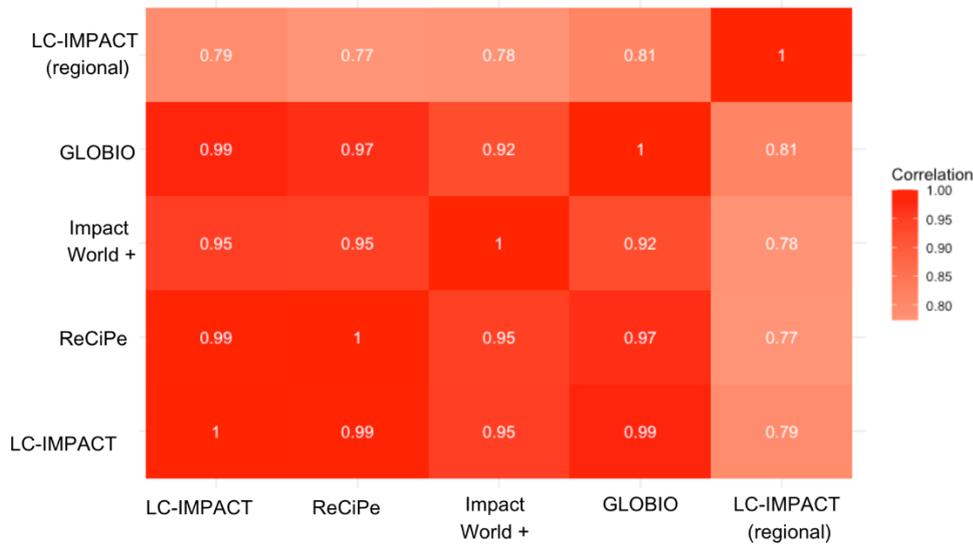
We did, however, see a difference between results when applying global characterisation factors versus region-specific factors. Results using region-specific LC-IMPACT characterisation factors displayed a lower average proportion of biodiversity footprint driven by GHG emissions than for the other methods (33%, compared to 60% average using LC-IMPACT global factors) and greater variance in results (CV = 63% using region-specific values versus 54% with global average) (Figure 3). Evidently, the decision to use global average or region-specific characterisation factors may drive differing overall results for the contribution of GHG emissions towards biodiversity footprints. Discrepancies in footprinting results in turn may alter corporate climate and biodiversity strategies, therefore warranting further attention (See Discussion for more detail) (Bromwich, 2024; Martínez-Ramón et al., 2025).

3.2. Evaluating the robustness of GHG emission pathways in biodiversity footprinting approaches

We further evaluate the robustness of GHG emission pathways across different biodiversity footprinting tools. We focus on 6 LCIA approaches from a review (Damiani et al., 2023), as well as 2 additional approaches published by the same authors since the original review (Iordan et al., 2023; Sif de Visser et al., 2023).

Across LCIA approaches, the basic framework to calculate the biodiversity impacts of GHG emissions remains the same. GHG emissions are translated into values of biodiversity impact through multiplication with 'characterisation factors' (Hellweg et al., 2023; Kuipers et al., 2025).

353   Characterisation factors are calculated through several steps (Figure 4). First, increases in
354   temperature driven by GHG emissions (°C/kg CO_2e) are quantified using global climate models
355   (Figure 4a). IPCC projections are used to estimate global temperature increases all of the
356   approaches (IPCC, 2014; Joos et al., 2013)(Table 1). Newer approaches also estimate ecosystem-
357   specific temperature increases based on Representative Concentration Pathways (RCPs)
358   (approaches 6-8, Figure 4a)(Table 1). Next, predicted temperature increases are linked to
359   biodiversity loss in terrestrial, freshwater and marine ecosystems. Values of biodiversity loss
360   caused by temperature increases are estimated using scientific literature (Figure 4b)(Table 1).
361   Approaches use highly similar literature to estimate the biodiversity impact of climate change: for
362   example, approaches 1-5 all use meta-analyses of biome distribution changes driven by global
363   temperature increases (Arets et al., 2014; Thomas et al., 2004; Urban, 2015).

364

365   Our LCIA approaches report biodiversity loss at the species level, using differing numbers of
366   drivers (Table 1). Many of the identified approaches report climate change-driven biodiversity
367   footprints in terms of Potentially Disappeared Fraction of species (PDF, 4 approaches), or Mean
368   Species Abundance (MSA, 2 approaches). PDF and MSA are commonly used indicators to
369   quantify losses in local or global biodiversity integrity driven by environmentally impactful activities
370   (Kuipers et al., 2025). Alternative approaches use species.year (local species loss integrated over
371   time) or PAF.year (Potentially Affected Fraction of species per year) metrics. Values of biodiversity
372   loss driven by climate change are totalled with other drivers of biodiversity loss, for example from
373   land use change. The number of drivers considered by LCIA approaches ranged from 1 to 9 drivers
374   (Table 1), although linear analysis showed that this is not a significant predictor for the proportion
375   of biodiversity footprints driven by GHG emissions (Section 3.1). This likely reflects shared
376   systemic biases due to the high levels of methodological similarity between approaches.

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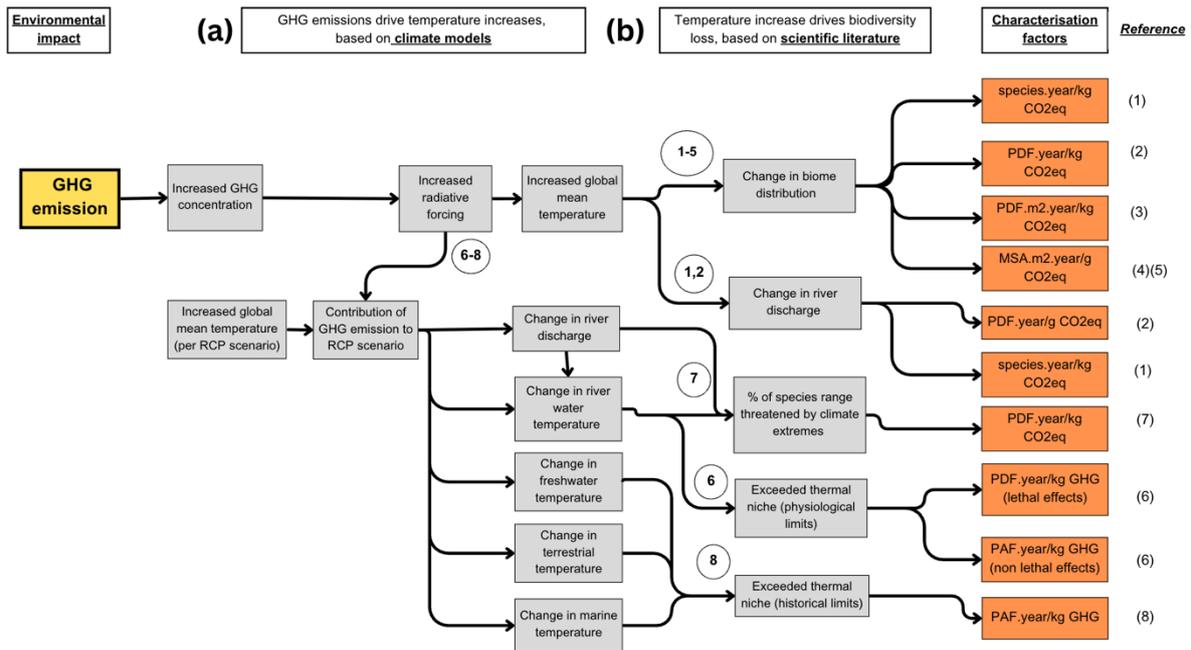
Figure 4: *Overview of pathways used to determine the biodiversity impact of GHG emissions. GHG emissions are translated into temperature increases (a) and biodiversity loss (b) using climate models and established scientific literature. Estimations for biodiversity loss per unit of emission are reported as characterisation factors (orange boxes). LCIA approaches are numbered according to Table 1 (Approaches 1-9). Circled numbers indicate the pathway used for each LCIA approach.*

	Approach	Unit	No. of drivers †	Key references	Ecosystems covered	Species specificity	Spatial resolution	Time horizon
1	ReCiPe	species. yr	9	Urban (2015), Hanafiah et al. (2011), IPCC (2013)	Terrestrial, freshwater	No	Global average	20, 100, 1000 years
2	LC-IMPACT(Verones et al., 2020)	PDF.yr	7	Urban (2015), Hanafiah et al. (2011), Xenopoulos et al. (2006), IPCC (2013)	Terrestrial, freshwater	No	Global average	100, 1000 years
3	IMPACT WORLD (Bulle et al., 2019)	PDF.m². yr	13	Thomas et al (2004), IPCC (2023)	Terrestrial	No	Global average	100, 500 years
4	Global Biodiversity Score (*Global Biodiversity Score: 2018 Technical Update | CDC Biodiversité*, n.d.)	MSA.loss.m²	2	Arets et al. (2014), Wilting et al. (2017), IPCC (2013)	Terrestrial, freshwater	No	Biome-specific	100 years

		unit	number of drivers	key references	ecosystems		spatial resolution	time horizon
5	Biodiversity Footprint Method (Wilting et al., 2017)	MSA.ha.yr	2	Arets et al. (2014), Wilting et al. (2017), IPCC (2013)	Terrestrial	No	Biome-specific	100 years
6	Water temperature and Freshwater Fish (Dan Li et al., 2022)	PDF.yr	1	Comte & Olden (2017), Barbarossa et al. (2021), IPCC (2013)	Freshwater	Yes	Region-specific	RCP dependent
7	Climate Change & Freshwater Fish (Sif de Visser et al., 2023)	PDF.yr	1	Barbarossa et al. (2021), IPCC (2013)	Freshwater	Yes	Region-specific	RCP dependent
8	CFs for GHG impacts on biodiversity (Iordan et al., 2023)	PAF	1	Trisos et al. (2019), IPCC (2013)	Terrestrial, freshwater and marine	Yes	Region-specific	RCP dependent; reported for 2050 and 2100

386

Table 1: *Comparison of selected LCIA approaches. Adapted from (Iordan et al., 2023). The unit of biodiversity loss ('unit'), number of drivers of biodiversity loss considered by each approach ("number of drivers", based on to Sanye Mengual et al (2022)) and key models and meta-analyses used to quantify climate-change driven biodiversity loss ("key references") are provided. Climate change-driven biodiversity footprints may be calculated for one or more ecosystem ("ecosystems"); species ("species specificity"); and GHGs ("GHG specificity"). The highest level of spatial resolution provided by each approach is highlighted ("spatial resolution"). Approaches with a global resolution, for example, provide global averages biodiversity impacts only. Results may be reported according to differing climate change scenarios ("sensitivity to future climate change") and time horizons ("time horizon"). Several approaches utilise Representative Concentration Pathways (RCPs), climate change scenarios to project future GHG concentrations, from RCP2.6 (very low future emissions) to RCP 8.5 (very high emissions scenario)*

There remain methodological differences between LCIA approaches (Table 1), however, which may drive variation and hinder comparability between LCIA results. These differences are driven by varying empirical bases and modelling choices. LCIA approaches use a different combination of climate models and scientific literature to determine characterisation factors (Table 1, 'Key References'). As such, different LCIA approaches include different ecological aspects, including ecosystem coverage, spatial resolution, time horizon and species specificity (see Table 1). Only one approach included terrestrial, freshwater, and marine environments, for example, highlighting the lack of empirical marine biodiversity data in the remaining LCIA approaches. This is surprising given the vulnerability of marine organisms to the effects of climate warming (Bongaarts, 2019). Similarly, most approaches calculated biodiversity impacts on a global scale due to a lack of

411 location-specific data (Table 1, Spatial Resolution). We expect this to be an important source of
412 variation, as shown when comparing LC-IMPACT regionalised and global values (Section 3.1).
413
414 Time horizons also differed between footprinting approaches, for example, with the impacts of
415 climate change modelled between 20 to 1000 years. Here, we used a time horizon of 100 years in
416 our analysis (Section 3.1.) Again, we would expect large changes in footprinting results based on
417 the time horizon, as the effects of climate change are cumulative over time. The majority of
418 footprinting approaches (Table 1, approaches 1–5), furthermore, estimate climate change-
419 driven biodiversity impacts as linear averages across species. More recent LCIA approaches
420 – particularly the GLAM approach – have clearly identified that species and regions are not
421 equally vulnerable to climate change (Table 1, approaches 6-8) (Iordan et al., 2023). This
422 represents an important methodological development and an improvement in data granularity
423 and has been up taken by the novel LCIA approach GLAM (UNEP/GLAM, 2023).
424
425 Evidently, selected LCIA approaches use a common conceptual framework to quantify the
426 biodiversity impacts of GHG emissions. LCIA approaches do however use varying empirical
427 bases and consider different ecological variables (species specificity, for example) which limits
428 their comparability and applicability. Perhaps most significant is the number of assumptions
429 and high level of uncertainty within LCIA calculations, as evident in the results of (Figure 3)
430 (Figure 4) and the lack of ecological variables in many of the approaches outlined in (Table 1)
431 (Bromwich et al., 2025). We comment upon the implications of this in the Discussion.
432
433 4. Discussion
434
435 Our results support the trend observed in previous biodiversity footprinting case studies, where
436 climate change is a dominant driver of an organisation's total biodiversity footprint (Bull et al.,
437 2022; Peura, Sami El Geneidy, et al., 2023; Peura, Pokkinen, et al., 2023). We find that on
438 average 47% of biodiversity footprints are driven by GHG emissions, with high levels of
439 correlation across approaches (Spearman's r >0.77) (Section 3.1).
440
441 There is a discrepancy, however, between modelled LCIA findings and other empirical
442 biodiversity assessments, for example, analysed the primary threats facing 8,688 species on
443 the IUCN Red List. Overexploitation and agriculture were identified having the greatest impact
444 on biodiversity currently, threatening 72% and 62% of the IUCN Red List species respectively.
445 Conversely, climate change is currently affecting 19% of species listed on the Red List. It is
446 therefore likely that LCIA results overestimate the current real-world contribution of GHG
447 emissions towards total biodiversity loss. However, a growing body of evidence indicates that

448   climate change is a major and increasing driver of biodiversity loss (Newbold, 2018; Trisos et

449   al., 2019; Urban, 2015), meaning that this discrepancy may change over time.

450

451   Methodological choices within LCIA models drive the discrepancy between biodiversity

452   footprinting results and observed data, as well as similarities in model outputs (Section 3.2).

453   LCIA approaches use limited and often overlapping empirical datasets to determine

454   biodiversity impacts, resulting in inherent biases in LCIA characterisation factors. As outlined

455   in (Table 1) there are a number of limitations in spatial specificity; temporal scales; species

456   specific responses to climate change; and ecosystems covered by LCIA approaches, driving

457   large amounts of uncertainty and systemic biases in results (Bromwich et al., 2024).

458   Furthermore, changes in species interactions are ignored by all approaches despite being a

459   key factor in community-level responses to climate change (Åkesson et al., 2021). Limitations

460   in representing the drivers of biodiversity loss may drive further uncertainty in LCIA

461   approaches. Invasive species and direct exploitation are not considered in any of the

462   approaches, for example, despite being key drivers of observed biodiversity loss (IPBES,

463   2019). Finally, LCIA approaches rely on models projecting future outcomes of climate change

464   (for example, species responses to altered biome distribution or temperature extremes (Figure

465   2b)). There is a large amount of uncertainty regarding the effects of future climate change,

466   which is inevitably reflected in LCIA models (Iordan et al., 2023; Payne et al., 2016; Rangwala

467   et al., 2021).

468

469   Therefore, we should be careful about the ability of current LCIA approaches to estimate the

470   biodiversity impact of GHG emissions, a sentiment echoed by similar studies (Bromwich et al.,

471   2025; Martínez-Ramón et al., 2025). Uncertainties in footprinting approaches may present a

472   major roadblock for their use in informing climate and biodiversity strategies. Overestimation

473   of climate impacts relative to other drivers of biodiversity loss, for example, could result in

474   biodiversity threats being viewed through the single myopic lens of climate change (Caro et

475   al., 2022). Incomplete characterisation of other drivers of biodiversity loss may also impede a

476   comprehensive assessment of biodiversity footprints and reduce the effectiveness of

477   sustainability strategies (Damiani et al., 2023; Iordan et al., 2023; Maier et al., 2019).

478

479   LCIA approaches are already developing to address some of the systemic biases highlighted

480   in our study. Newer LCIA methodologies such as Global Guidance for Life Cycle Impact

481   Assessment Indicators and Methods (GLAM) include are more spatially explicit and include

482   greater species specificity (UNEP/GLAM, 2023). Work is ongoing to include additional drivers

483   of biodiversity loss in LCIA assessment methods (plastic pollution and invasive species, for

484   example) which may help to reduce the overrepresentation climate change in footprinting

485   results (Corella-Puertas et al., 2023; Gjedde et al., 2024). Organisations also play a role in
486   improving biodiversity footprinting methodologies, including through research collaborations
487   with LCIA developers. Footprinting assessments should be undertaken in an iterative way,
488   enabling new results to be calculated as methods develop. Following existing guidance on
489   uncertainties will also be of use here, for example (Bromwich et al., 2025).
490
491   Despite the uncertainties, LCIA approaches remain one of the best available means to
492   estimate biodiversity loss across value chains and to support predictive strategical decision-
493   making in businesses. LCIA approaches are particularly important to communicate the effects
494   of climate change on biodiversity loss. Direct measurement approaches (site level biodiversity
495   assessments, for instance) alone are insufficient for quantifying impacts, as they may not
496   capture the impact of climate change which occurs over a relatively long timeframe.
497
498   Currently, the relationship between GHG emissions and biodiversity loss is not always made
499   clear within organisations. Integrated climate and biodiversity footprints may help to progress
500   this knowledge gap, informing strategies that tackle climate and biodiversity loss together. Our
501   results suggest that efforts to reduce the impacts of climate change may go some ways in
502   reducing organisational biodiversity impacts. Indeed, this has been shown when assessing
503   the biodiversity impacts of an organisation's climate strategy (Maddinson et al., 2025).
504   Organisations can leverage these findings, including through scenario analysis and decision-
505   support systems (Bull et al., 2022; Nature Positive Initiative, 2024). Sectors (and associated
506   products) identified here as having a high proportion of impacts driven by climate change (both
507   relative and absolute) should double down on their efforts to reduce GHG emissions in a
508   biodiversity-respectful way. Conversely, organisations can identify when reducing an
509   organisation's climate impacts has a negligible effect on absolute biodiversity impacts. Here,
510   additional biodiversity-specific strategies (focusing on land-use change or pollution, for
511   example) must be prioritised in order to achieve biodiversity goals. Cross-sectoral
512   benchmarking presents another interesting application of our approach, and has been
513   highlighted in the recent IBPES Business and Biodiversity report (IPBES, 2026).
514
515   Integrated climate and biodiversity impact assessment may further inform organisations to
516   meet the needs of the current and emerging sustainability reporting frameworks, such as
517   TNFD and CSRD. For one, footprinting enables organisations to better identify their 'material'
518   issues, as actions that produce a large amount of GHG emissions inevitably contribute heavily
519   to biodiversity loss. Indeed, the results provided in this paper could inform organisations for
520   example in their double materiality assessments as part of the EU CSRD regulation (EFRAG,
521   2025). If organisations have assessed that climate change is a material topic to them,

522 biodiversity should be identified as a material topic as well, and vice versa. Overall, footprinting
523 helps organisations to clearly assess and communicate their climate and biodiversity impacts,
524 enabling more effective performance measurement systems, supply chain management, and
525 risk assessment (Kedward et al., 2023; TNFD, 2025).
526

527 **5. Conclusion**

528

529 Organisations are increasingly interrogating their role as drivers of both climate change and
530 biodiversity loss. Here, we highlight the role of footprinting approaches in quantifying the
531 connections between, and charting progress towards, integrated climate and biodiversity
532 strategies. Our results indicate that climate change is a major contributor to biodiversity
533 footprints, presenting an opportunity to address climate and biodiversity impacts concurrently
534 in organisational strategies. However, modelling of climate-biodiversity interactions is clearly
535 still in its infancy, and current methodological limitations must be addressed if we are to apply
536 biodiversity footprinting in organisational reporting and strategy design.

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