

1 Comprehensive carbon footprint of Earth and 2 environmental science laboratories: implications 3 for sustainable scientific practice

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23 **Key Points:**

- 24 • We present a novel method to constrain the carbon footprint of research infrastructures
25 and attribute it to research institutions
- 26 • The comprehensive carbon footprint of six laboratories is mostly over 10 tCO₂e. p⁻¹, often
27 dominated by research infrastructures
- 28 • We argue that more sustainable science requires rethinking the deployment of new
29 infrastructures and abandoning the *fast science* ideal

30

31 Abstract

32 To limit global warming below 2°C, a drastic overall reduction from current CO₂ emissions is needed.
33 We argue that scientists should also participate in this effort in their professional activity and especially
34 Earth scientists, on the grounds of maintaining credibility and leading by example. The strategies and
35 measures to reach a low-carbon scientific activity require detailed estimates of the current footprint of
36 laboratories. Here, we present the footprint of six laboratories in Earth, environmental and space sciences,
37 representative of the AGU community, with a comprehensive scope also including international research
38 infrastructures. We propose a novel method to attribute the footprint of any research infrastructure to any
39 given research laboratory. Our results highlight that most laboratories have annual footprints reaching 10-
40 20 tonnes CO₂ equivalent per person (tCO₂e.p⁻¹), dominated by infrastructures and specifically satellites
41 in three cases (with footprints up to 11 tCO₂e.p⁻¹ or 60%), while air-travels and purchases remain within
42 the top three sources in all cases (2-4 tCO₂e.p⁻¹ or 10-30% each). Consequently, footprints related to
43 commuting and laboratory functioning, about 2 tCO₂e.p⁻¹ (20%) or less, are relatively modest compared
44 to infrastructures, purchases and air-travels. Thus, reduction measures ignoring infrastructures may not be
45 able to achieve reductions larger than 20 to 35% even with flight quotas and a substantial reduction of
46 purchases. Finally, we also discuss how a deeper transformation of scientific practices, away from a *fast*
47 *science* ideal, could make Earth and environmental sciences more sustainable and at the forefront of a
48 rapid and drastic social bifurcation.

49

50 Plain Language Summary

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53 needed. We argue that scientists should also participate in this effort in their professional activity
54 and especially Earth scientists, on the grounds of maintaining credibility and leading by example.
55 Here, we present the footprint of six laboratories in Earth, environmental and space sciences,
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57 research infrastructures. With a novel method to attribute the footprint of any research
58 infrastructure to research laboratory we find that most laboratories have annual footprints
59 reaching 10-20 tonnes CO₂ equivalent per person, dominated by infrastructures and satellites in
60 three cases, while air-travels and equipment purchases remain within the top three sources in all
61 cases. In comparison, footprints related to commuting and laboratory functioning, are relatively
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66 rapid and drastic social bifurcation.

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68

69 1. Introduction

70 The sixth series IPCC assessment reports underlined the need for an immediate and rapid decay
71 of greenhouse gases (GHG) emissions to mitigate current warming pathways and associated
72 cascading impacts (IPCC, 2022). Maintaining global warming below 1.5°C implies reducing
73 GHG emissions by ca 45% and 80% by 2030 and 2050, respectively, reaching an average of ca 2
74 tCO₂e.p⁻¹.yr⁻¹ on Earth in 2050 (see Fig TS.9 of IPCC, WG3, 2022). Although responsibilities
75 vary, it is clear that substantial reductions must affect all aspects of society, including academia.
76

77 Although various discourses of inaction (Lamb et al., 2020) are also present inside scientific
78 laboratories (Carbou and Sébastien, 2023), several lines of argument indicate that academia has a
79 specific responsibility to be exemplary in terms of reducing its GHG footprint. First, various
80 studies, including IPCC assessment reports, highlight that the political feasibility of a rapid
81 decarbonization of society likely requires various forms of social justice and reduction of
82 inequalities (Patterson et al., 2018; Stoddard et al., 2021; IPCC, 2022). It means that privileged
83 actors, including the academic sector, are arguably among those compelled to reduce first and/or
84 at an accelerated pace their GHG emissions.

85 Then, beyond their moral responsibility (Resnik and Elliot, 2016), the credibility and status of
86 the scientific community broadly working on ecological issues is linked to adopting exemplary
87 practices and lifestyles. Surveys showed for instance that GHG mitigation policies proposed by
88 climate researchers tended to be more or less supported by the public depending on the reported
89 carbon footprints of their proponent (low or high, respectively - Attari et al., 2016, 2019). This
90 emphasizes the importance for geoscientists to be leader in terms of reducing their own GHG
91 footprint.

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93 Efforts towards exemplary practices require a comprehensive assessment of ecological footprints
94 in academia, and an effort in building transparent and reproducible methods. Focusing on GHG,
95 the carbon footprint (CF) measures all direct and indirect GHG emissions (converted to CO₂-
96 equivalent emissions, CO₂e), more specifically scope 1 (direct process emissions), scope 2
97 (indirect emissions arising from the purchase of energy) and scope 3 (other indirect emissions
98 including the purchase of goods and services) according to the GHG protocol (WRI and
99 WBCSD, 2004). Methodologies to determine carbon footprint have been existing for more than a
100 decade and applied to various entities and at various scales (Wiedmann et al 2006, Wiedmann
101 and Minx, 2008). Such methods have then been applied to academic institutions, typically
102 research institutes or universities, but most often over limited scopes; the recent assessment over
103 470 French research laboratories by Mariette et al. (2022) for instance considered a restricted
104 scope 3 focused on mobility. Similarly, many studies on the academic CF have highlighted the

105 dominant share of air-travel (Achten et al., 2013, Le Quéré et al., 2015, Arsenault et al., 2019,
106 Mariette et al., 2022), and focusing on potential measures to reduce it (shift from air to train
107 travel, video call, reorganizing conferences; Langin, 2019). A focus on air-travel is relevant
108 because i) academic work is international in most fields, possibly with a link between scientific
109 visibility and mobility (Berné et al., 2022) and ii) because air travel is carbon intensive and iii)
110 relatively straightforward to quantify. Additionally, air-travel emissions are very unequally
111 distributed among scientists (Le Quéré et al., 2015, Arsenault et al., 2019, Blanchard et al., 2022,
112 Martin et al 2022b, Ben-Ari et al., 2023), making its regulation a potential example of reducing
113 emissions with a concern for social justice at the laboratory scale.

114 Nevertheless, beyond mobility, various efforts have attempted to quantify the carbon footprint
115 of other aspects of academia, such as that of product and service consumption (e.g., Ozawa-
116 Meida et al., 2013, Alvarez et al., 2014). A broad scope 3 assessment for the Norwegian
117 University of Technology and Science (NTNU), resulted in a total CF of $4.6 \text{ tCO}_2\text{e.p}^{-1}\text{.yr}^{-1}$ for
118 each of its 20,000 students with 16% from travels (of staff and students), 19% from energy use
119 and 35% from goods and services, underlining the need to account for a comprehensive scope 3
120 (Larsen et al., 2013). A compilation of CF estimates for 25 European universities between 2016
121 and 2020 reported between 2 and $7 \text{ tCO}_2\text{e.p}^{-1}\text{.yr}^{-1}$ when mostly limited to scope 1 and 2 and
122 mobility, reaching $10\text{-}30 \text{ tCO}_2\text{e.p}^{-1}\text{.yr}^{-1}$ when including a more comprehensive scope 3
123 (ALLEA, 2022). Very recently, an estimation of the CF of purchases for more than 100 French
124 research laboratories concluded that purchases was often the largest share of the footprint, about
125 50% with $2\text{-}4 \text{ tCO}_2\text{e.p}^{-1}\text{.yr}^{-1}$, and that laboratories had a typical carbon intensity of 0.32 ± 0.10
126 $\text{tCO}_2\text{e/k€}$ (De Paepe et al., 2023).

127 CF estimates for large/international research infrastructures have also been released, including
128 satellite and ground telescopes for astronomy (Knödlseeder et al., 2022), the GRAND
129 astrophysics project (Aujoux et al., 2021) or the infrastructures used for particle physics such as
130 the CERN (European Center for Nuclear Research, Bloom et al., 2022, Janot et Blondel, 2023).
131 These CF estimates often relied heavily on scope 3 emissions, which could represent a very large
132 share of the annual CF of research institutes when added to their in-situ footprint. A
133 comprehensive CF estimate made for the largest French research institute in astronomy and
134 astrophysics (IRAP) further found that the contribution of satellite and ground observatories
135 amounted to 38% and 18% in 2019, while air-travels and purchases represented lower
136 contributions with 16% and 18%, respectively (Martin et al., 2022a). The magnitude of the CF,
137 nearing $30 \text{ tCO}_2\text{e.p}^{-1}\text{.yr}^{-1}$ for the 263 employees of this laboratory, made the authors to suggest
138 that substantial reorganization of research practice and goals were urgently needed in astronomy
139 and astrophysics.

140 However, such a comprehensive assessment for laboratories in Earth and Environmental
141 Sciences is among the missing pieces to help understanding i) how to advance knowledge on
142 Earth system processes (including the ongoing climate and ecological crisis) while adopting
143 sustainable research practices and ii) how Earth and Environmental scientists can be exemplary,
144 in the prospect of efficiently promoting awareness and actions to face the ecological
145 emergencies.

146 To address these research challenges, we present here a comprehensive CF assessment for six
147 research laboratories which formed the Observatoire Midi-Pyrénées in 2019, a large French
148 public research institute of Earth, Environmental and Space Sciences. Several of these
149 laboratories have the specificity to rely on substantial use of satellite infrastructures.

150

151 **2 Data and Methods**

152 2.1. Presentation of the studied laboratories

153 Staff and activity data of the 6 laboratories composing the Observatoire Midi-Pyrénées (OMP,
154 www.omp.eu) in 2019 are summarized in Table 1. Here we briefly describe their scientific focus.

155 The CESBIO (Centre d'Etude Spatiale de la BIOSphere) focuses on the continental surfaces and
156 more specifically on soil/vegetation/atmosphere interactions, with a strong expertise in remote
157 sensing data. The GET (Géosciences Environnement Toulouse) is a laboratory with prime
158 expertise in geology, geophysics, geochemistry, hydrology and environmental processes in the
159 critical zone. The IRAP (Institut de Recherche en Astrophysique et Planetologie) has broad
160 expertise in observing, modeling and instrumenting all aspects of astrophysics and planetology.
161 The LAERO (Laboratoire d'Aérodynamique) focuses on the physics and chemistry of the lower
162 atmosphere through observation and numerical modeling. The LEFE (Laboratoire Ecologie
163 Fonctionnelle et d'Environnement) focuses on ecosystem health, ecosystem services and
164 ecological responses to global changes. The LEGOS (Laboratoire d'Etude en Géophysique et
165 Océanographie Spatiales) focuses on the water cycle in the broadest sense, with the physics of
166 the oceanic, hydrological, cryospheric and atmospheric components, including coastal and
167 climatic components, as well as marine biogeochemistry and geochemistry.

168 For each laboratory we only consider persons with continuous contracts over the whole of 2019,
169 including PhD and postdoctoral researchers, administrative and technical support staff (up to
170 research engineers), and permanent research and teaching staff. Researchers are employed with
171 national institutes with only optional teaching duties, while lecturers and professors (and
172 equivalents) are employed by the university and have a mandatory teaching load.

173 All six laboratories are joint research units supported by both the French National Center for
 174 Scientific Research (CNRS), and the University Toulouse 3 Paul Sabatier (UT3). Additional
 175 supports for the various laboratories includes the National Center for Space Studies (CNES), the
 176 National Research Institute for Sustainable Development (IRD), the National Institute of
 177 Research for agriculture, food and environment (INRAE) and the National Polytechnical
 178 Institute of Toulouse (INP). We recall that all results from IRAP have been published in Martin
 179 et al., (2022a, b), following Knödlseeder et al. (2022) for research infrastructures, and here we
 180 simply recast their figures for comparison with the other laboratories of the OMP and to have a
 181 broad discussion about Earth, Environment and Space Sciences.

Laboratory	CESBIO	GET	IRAP	LAERO	LEFE	LEGOS
Professors (University employees)	16	38	54	20	32	9
Researchers (employed by other public institute)	16	74	62	17	10	38
Support staff	34	52	78	34	35	44
PhD/Post-doc	44	86	69	19	63	30
Considered Infrastructures	Sat	Sat + Sea	Sat + Obs	Sat + Air	Sat	Sat + Sea
Professional travels, in 10 ⁶ km	0.7	3.8	6.4	1.0	0.9	4.8
Expenses, in 10 ⁶ €	1.1	1.8	3.7	1.0	0.6	1.6
Travels (tCO ₂ e)	169	612	1179	174	178	742
Purchases (with IT) (tCO ₂ e)	415	755	1426	464	258	424
Total in-situ (tCO ₂ e)	684	1868	3340	952	704	1460
Total with RI (tCO ₂ e)	1968	2341	7440	1092	708	2581
Total in-situ (tCO ₂ e.p ⁻¹)	6.2	7.8	12.7	11.0	5.2	12.1
Total with RI (tCO ₂ e.p ⁻¹)	17.9	9.8	28.3	12.6	5.2	21.4

182

183 **Table 1:** Summary of activity and key sources of CO₂ emissions for the six laboratories
 184 affiliated to the OMP in 2019. Total Expenses are excluding expenses for professional travels.
 185 Abbreviations as following, IT= Information Technology, RI=Research Infrastructure,
 186 Sat=Satellites, Obs=ground astronomical observatories, Air=IAGOS infrastructure, Sea= IODP
 187 (for GET) and PIRATA (for LEGOS) infrastructure and use of other large research ships.

188 2.2. GHG budget method and scope

189 To assess GHG emissions, we followed standard procedure in which ‘activity data’ that quantify
 190 the usage of a given source (e.g., energy consumption in kilowatt hours, or travel distances in
 191 kilometers, etc.) are multiplied by associated ‘emission factors’ (EF) that quantify the unitary

192 carbon footprint of each source (e.g., electricity production or air-travel) (Table 1). To constrain
193 the emissions of commuting, electricity, gas, cooling fluids, and professional travels we followed
194 the standardized approach proposed by Mariette et al. (2022), and used the GES1.5 tool. For air-
195 travels we present results including the indirect radiative forcing of condensation trails, which
196 are equivalent to doubling the footprint derived from CO₂ only (Mariette et al., 2022). Note that
197 professional travels also includes train and car and internal commuting for laboratories with
198 facilities in several towns.

199 Additionally, we consider the emissions related to expenses (i.e., the GHG emissions resulting
200 from the life-cycle of products or services bought by the laboratory), by considering financial
201 listings and attributing a financial EF, in kgCO₂e.k€⁻¹, to different categories, such as food,
202 service, clothes, furniture, electronics, machines (e.g., Ozawa-Meida 2013, Alvarez 2014, De
203 Paepe et al., 2023). Purchases are categorized by the administration of French public research
204 and education using a classification called NACRE. For each relevant NACRE category
205 (identified by a code) we have extracted an average emission factor from the Base Carbone
206 database of the French Environment and Energy Management Agency (ADEME, 2023) (as in
207 Martin et al., 2022a, b, see Table S1). This is a simplified approach compared to the one recently
208 described in De Paepe et al., (2023), still under development at the time of data collection and
209 analysis. Thus, future work should likely apply their emission factors more robustly evaluated,
210 and easier to use as they are now implemented in GES1.5. Nevertheless, as we show later, our
211 results are very consistent with this updated method.

212 We separated from these listings all expenses under NACRE codes starting by “I” which relate
213 to Information Technology (IT), (i.e., screen, printers, computers, components ...), to assess
214 their specific importance, and we excluded all expenses related to professional travels (flights
215 and hotels) which are counted based on an alternative method.

216 Following Martin et al. (2022a, b), we further extended the scope of our assessment to a few
217 more items, even if they could not all be retrieved for the six laboratories (Table S2). We
218 assessed the emission associated with external data storage and computation, and food consumed
219 on campus, making use of an online poll sent to the staff to constrain annual activity in each
220 laboratory in terms of CPU.hour, terabytes (Tb) and total number of meals of various diets. Most
221 external computing in the studied laboratories is performed in France and thus we used an EF of
222 3.6 gCO₂e per CPU.hour relevant for a typical computing center in France (Berthoud et al.,
223 2020). For 1 Tb of data stored during a year in a datacenter, the EF is typically of 12 kgCO₂e in
224 France but the median for other countries with less favorable electricity mix is rather 35 kgCO₂e
225 (Charret et al., 2020). In the poll, the location of the datacenter was not always filled and beyond
226 France, various country were reported, so for simplicity we used an intermediate EF of 25

227 kgCO₂e per Tb. Last, for food we used EFs of 2.6, 1.1 and 0.5 kgCO₂e per classic, flexitarian
228 and vegetarian meal (ADEME, 2023). We also considered water consumption, considering 0.132
229 kgCO₂e.m⁻³ (ADEME, 2023), and waste based on estimates of the volume and frequency of
230 recollection for various waste type (mixed, plastic and paper - Martin et al., 2022b). Last, given
231 that in financial listings hotel nights are often included into a general travel expenses code
232 NACRE (i.e., bundled with train or flight tickets), which is excluded from the financial
233 conversion, we instead used more detailed travel listings to compute the footprint associated with
234 hotel nights spent during travel emissions. Thus, we used the number of nights in missions
235 multiplied by country-dependent EFs in kgCO₂e.night⁻¹ (UK Government, 2020). However, long
236 missions lasting several weeks dominate the total number of nights, while they may not only rely
237 on hotel accommodations but may involve camping in the field or other accommodations with
238 smaller footprints such as flat renting. As a result, we considered as an upper bound the
239 conversion of all nights with their EFs, and as a lower bound the conversion of all nights during
240 mission of less than 20 days, setting accommodation footprint of longer missions to zero. We
241 thus consider as a best estimate a conversion where we cap to 20 the number of nights spent in
242 hotels for any mission. Last, we note that this estimate may be slightly over-estimated for two
243 reasons. First, because the EF are for one room independently of the number of users in the
244 room, so in case of shared room we may have overestimated the number of nights, and second
245 because the EFs released by the UK government for later years (2022, 2023) tend to be 30%
246 smaller than the ones of 2019, which may both reflect change in methodology and actual
247 reduction of hotel footprint.

248 Building construction was not counted as it was done more than 30-40 years ago for most parts
249 of the buildings at OMP, and thus could be considered amortized and not relevant for the 2019
250 budget.

251

252 2.3. Carbon footprint of research infrastructures

253 Beyond purchases, we proposed here a new methodology to account for another potentially
254 major source of green-house gases: the use by Earth scientists of large, international, research
255 infrastructures. Namely, we propose a versatile methodology which we apply to a large array of
256 satellite infrastructures allowing Earth observation from space, but also to a few more
257 infrastructures specifically used by some of the studied laboratories, and relying on ships or
258 aircrafts. We again stress that beyond satellite infrastructures, we do not claim to be exhaustive
259 in estimating the footprint of research infrastructures used by the studied laboratories. The reason

260 is that many of the research infrastructures in the domain of Earth observation are distributed
 261 over many sites, laboratories and institutions. Thus, quantifying their total footprint remains very
 262 challenging. As a result, whereas our estimate for the footprint of satellite infrastructures is likely
 263 a representative first-order estimate, the estimates for other infrastructures, is not exhaustive and
 264 thus likely to be a lower bound only. Some elements of uncertainties associated to this limit are
 265 discussed in 4.1.

266

268 2.3.1 General approach

269 Our new methodology is an adaptation of the one proposed by Knödlseeder et al., 2022, targeted
 270 at astronomical space missions, including satellites, rovers and space probes.

271 Inspired by this pioneer study, we estimate the total footprint of any infrastructure, i , for a given
 272 laboratory, l , over a given time period Δt , with the following formulas:

273

$$274 \quad F(i, l, dt) = F(i) \frac{Ml(i, l) Af(i, l, \Delta t)}{M(i, \Delta t)} Ss(i), (Eq. 1)$$

276 where: $F(i)$ is the annual GHG footprint of infrastructure i ; M and Ml are the numbers of all
 277 scientific publications and the ones with at least one co-author from the laboratory l ,
 278 respectively, during Δt using the infrastructure i ; Af is the average fraction of author affiliated
 279 with lab l within the Ml manuscript sub-sampled; Ss is the share of the infrastructure used for
 280 research purposes.

281 Thus, for each infrastructure the three terms we must estimate represent: (i) its footprint based on
 282 its construction or activity data (in tCO₂e.yr⁻¹), (ii) the share of the studied lab relative to all
 283 other labs (from 0 to 1), and (iii) the share of usage between research and other usage (from 0 to
 284 1). This approach is particularly adapted for infrastructures which produce and deliver data to a
 285 broad community, for which the share of usage cannot be specifically attributed to any user, in
 286 contrast to infrastructures for which each user has to declare a certain usage, for example beam
 287 time for a synchrotron, CPU time for a super computing center (Berthoud et al., 2020), or hours
 288 of observation in an astronomical observatory (Knödlseeder et al., 2022).

289 $F(i)$ and $Ss(i)$ are estimated for each infrastructure in the following subsections, and we only
 290 detail here the general algorithm we developed to determine the share of the lab among the world
 291 scientific community (Supplementary Information). Given the various disciplines of the studied
 292 laboratories, and the fact that infrastructures do not necessarily maintain a publication list, we

293 propose to use, by default, a generalist bibliographic database, the Clarivate Web of Science
294 (WOS) database (See Supplementary Methods). Given the size of the database and the number
295 of authors, we also simplify the approach of Knödlseeder et al., 2022, by extracting first
296 automatically $M(i, \Delta t)$ and $Ml(i, \Delta t)$ by querying the database to retrieve all work relating to the
297 infrastructure i , over the period Δt , with or without a constraint on the authors' affiliations. Then,
298 to avoid attributing several times emissions when an article using a satellite is signed by authors
299 from several laboratories, we export the metadata of the $Ml(i, \Delta t)$ articles and extract the mean
300 proportion of individual authors from the studied laboratory among those ($Af(i, l, \Delta t)$). Authors
301 with multiple affiliations were counted as fraction as if its part would be split between several
302 institutions (see Supplementary Information). We expect the number of publications associated
303 with one infrastructure in a given laboratory to be highly variable on an annual basis. Thus, we
304 assume that a 5-year average allows a more representative estimate of the share of the
305 infrastructure footprint that should be given to the lab, and thus we used $\Delta t=2015-2019$ for all
306 infrastructures. For IAGOS, IODP and PIRATA which maintain a dedicated database of
307 scientific publications, we applied our method on these databases in addition to the WOS
308 database. We assume the dedicated databases to be more comprehensive and accurate, and use
309 them for the final footprint attribution while we give the WOS results for comparison and
310 discussion only.

311 2.3.2 Satellite infrastructure

312 Using only scientific publications to determine the proportion of usage to attribute to each lab,
313 implicitly assumes the whole footprint of any mission is only shared among the research
314 community. This was expected for astronomical instruments but it is not obvious for Earth
315 observation satellites. Thus, we excluded all satellite missions which are primarily designed for
316 non-scientific purposes, typically weather forecast satellite (EUMETSAT, METEOSAT and
317 GOES series for example) or GPS constellations, for which scientists are likely a negligible
318 proportion compared to all other public and private users. We also limit ourselves to the main
319 missions with specific scientific instruments and did not considered the large number of
320 “national” observation satellites (such as CBERS, KOMPSAT, etc).

321 As a result, we consider 44 Earth Observation satellite missions, several containing
322 constellations or successive satellites (e.g., the Landsat series), amounting to 82 individual
323 satellites (Table S3). Most of these missions are mostly scientific, with restricted access and
324 usage limited to specialists, but not all of them. Some of them produce broadly used and broadly
325 accessible data (e.g., the Landsat, SRTM or Sentinel missions; N=11 out of 44, see Table S3)
326 designed to be used by private companies, and public institutions, which are increasingly doing

327 so for various applications. Hence, there was a need for these missions to determine their S_s , the
328 share of the total footprint attributable to the scientific community. For the Sentinel missions 30-
329 60% of the 2019-2022 downloads on the ESA platforms were for research (Copernicus, 2024).
330 However, it is likely that a large share of downloads are done through other distributors such as
331 Amazon AWS, or Google Earth Engine, where the proportions of non-scientific users may be
332 larger. Thus, S_s for these missions may range from 0 (e.g., a negligible share for scientists, as
333 assumed for weather forecast or GPS satellites) to about 0.6 following the ESA report, so we
334 used a central estimate $S_s=0.4$, as well as lower and higher values for discussion.

336 To derive $F(i)$, we collected satellite launch mass and converted it with life-cycle emission factor
337 of 50 (+/-10) tCO₂e.kg⁻¹, and dividing by the time in years between mission launch and the year
338 of interest 2019 (Knödlseeder et al., 2022, Wilson, 2019). For most missions we could not
339 retrieved full mission cost and thus we focus on the estimates derived from launch masses (Table
340 S3). The SRTM mission is an exception as it was fully operated through a Space Shuttle mission
341 for which the weight factor cannot be applied and only the financial estimate was used and
342 converted with and EF of 140 tCO₂e.M€⁻¹. For recent missions, launched less than 10 years
343 before 2019, we assumed the emissions should nevertheless be distributed over a minimal
344 timescale, $T_{min}=10$ yr, consistent with the approach of Knödlseeder et al. (2022). The impact of
345 choosing $T_{min}=20$ yr on our results is also discussed.

346

347 2.3.3 IAGOS Infrastructure at LAERO

348 The In-Service Aircraft for Global Observation System (IAGOS) infrastructure relies on
349 commercial aircraft embarking instruments measuring atmospheric composition and
350 meteorological variables along the flight (Petzold et al., 2015). The emission factor for scientific
351 instrumentation on-board commercial flights is computed based on the "cost of weight" approach
352 (IATA, 2011). This approach is widely used for estimating the fuel consumption due to
353 additional weight embarked on airliners. It is preferred to emission factors for air cargo (which
354 are one order of magnitude larger), because scientific observations is not the purpose of
355 commercial flights but take advantage of existing airlines (emission factors for air cargo or air
356 travel include in supplement emissions due to the weight of the aircraft itself, its manufacturing,
357 airport infrastructures, etc.). Assuming a typical cost of weight of 0.035 kg of kerosene per kg of
358 extra freight and per flight hour, and an emission factor of 3.83 kgCO₂e kg⁻¹ for kerosene
359 (ADEME, 2023), we obtain an emission factor of 0.133 kgCO₂e (kg freight)⁻¹ (flight h)⁻¹. This
360 value only includes for CO₂ radiative forcing but not for the additional effects of flight contrails.

361 Following Mariette et al. (2022) to this goal, we finally double this emission factor, up to 0.266
362 kgCO₂e (kg freight)⁻¹ (flight h)⁻¹ to be consistent with our other estimates of air-travel footprint.
363 The IAGOS instrumentation has a typical weight of 120 kg and about 20,000 h were flown in
364 2019 (representative of the few previous years) with IAGOS on board, yielding a total footprint
365 of 640 tCO₂e.yr⁻¹.

366 Querying WOS with the keyword 'IAGOS', for 2015-2019 yielded 47 publications worldwide
367 and 20 with at least one author from LAERO. The average author fraction of these publications
368 was 0.45 which indicates that a fraction 0.19 of the total footprint should be attributed to
369 LAERO. The dedicated publication database (IAGOS, 2024) report 93 publications worldwide
370 over 2015-2019 and 40 with an author from the LAERO, with a mean author fraction of 0.36
371 yielding a global share of 0.15, quite consistent with the WOS estimate. Retaining this latter
372 share we obtain a footprint of 96 tCO₂e for the LAERO.

373 Note that the LEGOS is also part of another infrastructure with a similar design, called SSS for
374 Sea Surface Salinity, but for which we could not performed an overall assessment (see SI).

375

376 2.3.4 Oceanographic missions

377 Two laboratories, the GET and the LEGOS, are frequently involved with oceanographic
378 missions, which involve large international consortia. For example, in 2019, seven agents were
379 funded by the GET to spent 2 months each, and 3 agents from the LEGOS spent a total of 84
380 days, on oceanographic ships operated by the IODP (Integrated Ocean Discovery Program) and
381 the PIRATA (Prediction and Research moored Array in the Tropical Atlantic) programs,
382 respectively. Such participation is regular for these laboratories. We follow the same approach as
383 for the satellite infrastructure, using Eq. 1 and assuming $S_s=1$ for both infrastructures, and
384 calculating the average annual footprint of the infrastructure. Typically, we estimate the fuel
385 consumed by the ships for each expedition, in tons or m³, and then convert it with an emission
386 factor for diesel marine fuel of 3.75 kgCO₂e.kg⁻¹ (ADEME, 2023). For some infrastructure
387 depending on available information we also assess, air-travels, freight and purchases but found it
388 to always be minor relative to the fuel used by ships.

389 2.3.4.1 IODP footprint and share attributed to the GET

390 For IODP, 85% of all missions are on board the Joides Resolution which use of 33, 17 and 7,
391 tons of fuel per day for all its activities, during transit, station and harbor phases, respectively, as
392 reported by the crew. Given the daily statistics of activity over 2013-2023 (IODP, 2024a), we

393 estimate an annual footprint of 24 ktCO₂e.yr⁻¹ for the Joides alone (Table S4). The remaining
394 15% of missions are operated by a Japanese drilling ship and by 3rd parties missions coordinated
395 by a European consortium for which we could not gather detailed information but simply assume
396 similar footprint which would rise the total by 15% to 27.5 ktCO₂e.yr⁻¹. At first order, the
397 footprint of flights taken by scientists to join the boat, may add about 1 ktCO₂e.yr⁻¹ (see
398 Supplementary Methods), yielding a total footprint of 28.4 ktCO₂e.yr⁻¹.

399 Querying the WOS database with the keyword 'IODP' over 2015-2019 we found 4 scientific
400 publications for the GET and 577 worldwide. Accounting for a mean author fraction we would
401 obtain a share of 0.065%. Ignoring the IODP data proceedings and non-English publications, we
402 found 10 publications including a GET author out of 1922 in the IODP dedicated publication list
403 (AGI and IODP, 2024). This yields an author fraction of 0.089% representing 25.3 tCO₂e.yr⁻¹
404 for the GET. We note that the publications attributed to GET by the two queries do not
405 completely match, but that the two databases yield similar mean author fraction over the 2015-
406 2019 period.

407

408 2.3.4.2 PIRATA footprint and share attributed to the LEGOS

409 The PIRATA program involves Brazil, the US and France, and is about deploying and
410 maintaining a network of moored buoys in the Tropical Atlantic. There are currently 18 buoys
411 points and regular oceanographic missions are conducted to maintain them and do associated
412 measurements. Limiting our analysis to 2015-2019, we retrieved the cruise duration, typically
413 around 30 days per year per country, and embarked scientists dedicated to PIRATA (typically 6
414 to 16 depending on the mission), yielding a total of 5444 person.day at sea (PIRATA, 2024a).
415 These numbers ignore embarked scientists dedicated to other research infrastructures, such as
416 AEROSE during US expeditions for example.

417 Based on technical data from the French Scientific ships and reported data for the Brown US
418 ship, we consider a typical fuel consumption of 0.5 m³.p⁻¹.d⁻¹ equivalent to 1.6 tCO₂e.p⁻¹.d⁻¹
419 (See Supplementary methods) leading to a 2015-2019 average of 1.7 ktCO₂e.yr⁻¹ (Table S4).
420 Then air-travels appear as negligible, but we estimate freight to add 0.1 ktCO₂e.yr⁻¹ and the
421 instrumented buoys themselves to add 0.4 tCO₂e.yr⁻¹, yielding a total annual footprint of the
422 PIRATA infrastructure of 2.2 ktCO₂e.yr⁻¹ (See Supplementary methods).

423 For 2015-2019, Web of Science retrieves only six publications worldwide out of which five have
424 LEGOS authors, yielding an author share of 15%, while the PIRATA dedicated publication list
425 details 19 publications with at least one LEGOS author out of 99 in total (NOAA, 2024),
426 yielding a mean author share of 5%. In this case the WOS database clearly under-samples the

427 literature and bias up the results, while with the dedicated publications list we obtain an
428 infrastructure footprint of 110 tCO₂e.yr⁻¹ for the LEGOS.
429

430 2.3.4.2 Other Oceanographic missions

431 In addition to these contributions to international research efforts some researchers may join ship
432 cruises for their own research purpose which means their entire emissions should be attributed to
433 their laboratory. For example, in 2019 at GET, one round trip mission to the Kerguelen islands
434 was done by a researcher, which we estimate to emit 50 tCO₂e (Supplementary information). In
435 2019 at LEGOS, there was the MOANA-MATY 2 mission, a cruise for the SURVOSTRAL
436 program and two missions with unknown motives, with one scientist at sea for 24, 10, 9 and 6
437 days, respectively. Assuming the emission factor of PIRATA cruises holds (1.6 tCO₂e.p⁻¹.d⁻¹,
438 SI) yield a total footprint of 78 tCO₂e. Given we could not find publications list nor consistent
439 mention of the two former programs, we simply attribute the whole footprint to the LEGOS.

440 LEGOS also manages other ship-based observatories such as SONEL, and occasionally performs
441 works in the Southern French territory, but we did not retrieve detailed information for 2019 and
442 recommend a future consolidation of the overall footprint of research cruises.

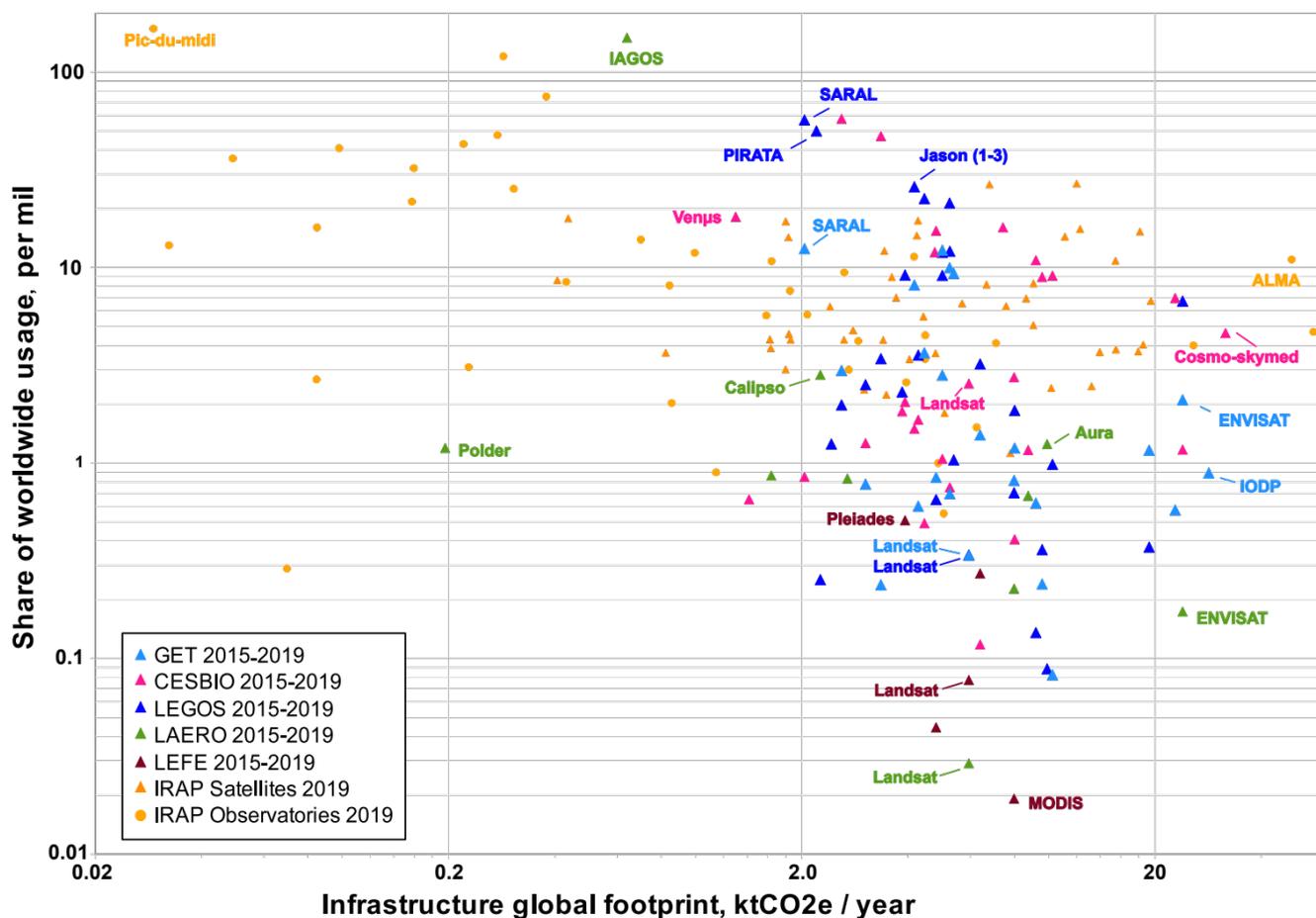
443

444 **3 Results**

445 3.1 Carbon footprint of research infrastructures

446 We start with synthesizing our results on international research infrastructures that is the main
447 novelty of our study. With our method, we estimated the annual CF of 44 satellite missions
448 relevant to the Earth and Environmental Sciences, considered as individual infrastructure, to be
449 ranging from 0.3 to 31 ktCO₂e.yr⁻¹ with a median of 5 ktCO₂e.yr⁻¹. The global share of
450 attribution to laboratories are typically between 0.01 to 1% with a few outliers above 5% (Fig
451 1). These values broadly agrees with estimates for astronomical satellite infrastructures
452 (Knödseder et al., 2022), and to some extent to astronomical ground observatories, though the
453 latter span a broader range of footprint (0.03 to 30 ktCO₂e.yr⁻¹). We find no clear correlation
454 between the age (first launch) of the satellite infrastructure and its footprint. This reflects the
455 diversity of satellite weights through time and the fact that many old missions (amortized over
456 long period) have had mission extensions (e.g., Landsat, ALOS, Jason) with successive launches
457 increasing the total footprints. Overall, the 44 satellite missions considered in this study represent

458 6.3 MtCO₂e (Table S3), similar to the 4.9 MtCO₂e estimated for the Y astronomical space
 459 missions (Knödlseider et al., 2022).



460 **Figure 1:** Share of usage of infrastructures by each laboratory against the annual footprint of the
 461 studied research infrastructures. Several examples of infrastructures are named for references.
 462 For IRAP we differentiate observatories and satellites, as derived with a similar methodology
 463 (Knödlseider et al., 2022), while for the other laboratories, all infrastructures are satellites (See
 464 Table S3) except IODP, PIRATA and IAGOS.

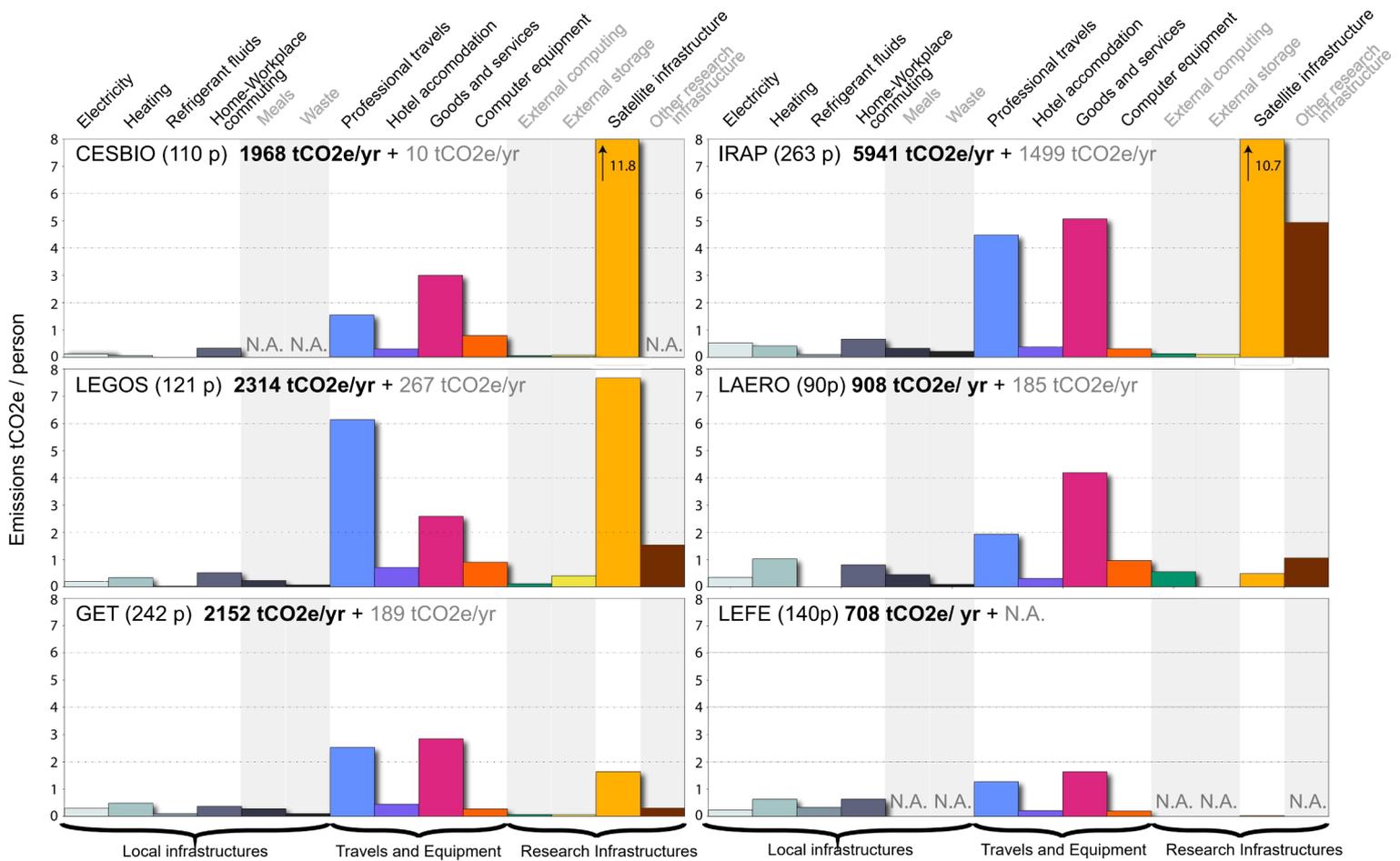
465

466 Turning to the aggregated footprint of all satellite infrastructures for Earth observation, it appears
 467 as the dominant share of the CO₂e budget for three laboratories, IRAP, CESBIO and LEGOS,
 468 equivalent to 2800, 1284 and 933 tCO₂e.yr⁻¹, respectively, which is typically 40-65% of the total
 469 CF (Fig 2, 3). LEGOS and CESBIO rely heavily on satellite infrastructures, as reflected by their
 470 numerous publications (263 and 417 over five years, respectively) with keywords associated
 471 with a broad diversity of satellites, nearly 30 missions out of 44 (Table S3). For GET and
 472 LAERO, where fewer researchers rely on satellite observations, we retrieve 150 and 43
 473 publications associated with 24 and 9 missions for the 2015-2019 period, which represents 1.6
 474 and 0.5 tCO₂e.p⁻¹.yr⁻¹ or 398 and 45 tCO₂e.yr⁻¹ for the whole laboratory, respectively. For the

475 LEFE with only 5 publications associated with 5 satellites over 5 years the footprint is below 5
 476 tCO₂e.yr⁻¹ or 0.05 tCO₂e.p⁻¹.yr⁻¹.

477 Turning to other infrastructure, for GET, IODP and ship missions to the sub-Antarctic region
 478 result in a moderate footprint of 25 and 50 tCO₂e, respectively, adding 0.3 tCO₂e.p⁻¹.yr⁻¹ to the
 479 laboratory. For LEGOS, the PIRATA infrastructures and other oceanographic missions have an
 480 estimated footprint of 110 and 78 tCO₂e, respectively, representing 1.6 tCO₂e.p⁻¹.yr⁻¹ together.
 481 For the LAERO, the IAGOS infrastructure is estimated to be 96 tCO₂e.yr⁻¹ or 1.1
 482 tCO₂e.p⁻¹.yr⁻¹.

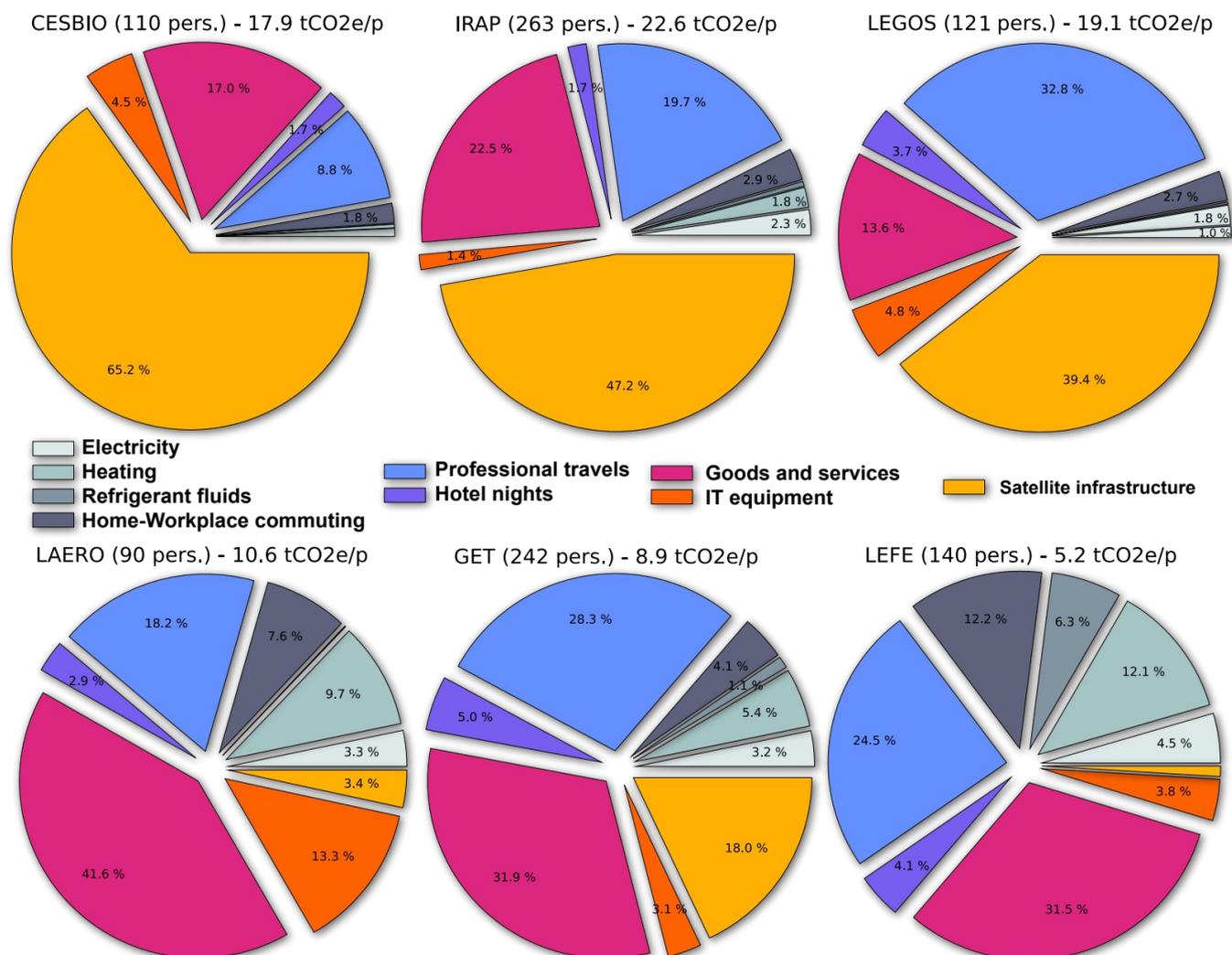
483 These infrastructures display footprint and attribution in the broad range of the satellite
 484 infrastructures and of astronomic infrastructure (Fig 1) and are consistent with the typical
 485 footprint attributed to one laboratory for individual satellite mission, mostly between 10 and 100
 486 tCO₂e.yr⁻¹ (Table S3).



488 **Figure 2:** Carbon footprint in tCO₂e per person, grouped by sectors, differentiating, local
 489 infrastructures, research activities and international research infrastructures. For each laboratory

490 sources that could be estimated homogeneously for all labs have a white background and their
 491 total footprint is in bold black, while sources in shaded areas (with a reported total in grey)
 492 sources that could not be estimated homogeneously for all labs and which are thus excluded from
 493 Figure 3.

494



496 **Figure 3:** Proportions of the carbon footprint for the sources that could be consistently estimated
 497 for each of the six laboratories of the OMP.

498

499 3.2 Carbon footprint of laboratory purchases

500

501 Purchases are also a major share of the CF, between 2 and 5 tCO₂e.p⁻¹.yr⁻¹ for the studied
 502 laboratories (Fig 2), which typically represent 15 - 40% of the whole footprint (Fig 3),

503 highlighting the need to consider a comprehensive scope 3 emissions when estimating GHG
504 budget for research laboratories (De Paepe et al., 2023). The emissions are typically distributed
505 over a broad range of activities including services, machines and equipment for experimental
506 research, repairs and maintenance, experimental supply and to a minor extent general supply
507 (food, furniture, etc). IT equipment is also representing a substantial share, amounting to a
508 minimum of 5-10% of the purchase emissions (i.e., 0.15 to 0.3 tCO₂e.p⁻¹.yr⁻¹) and up to 0.9 and
509 1.4 tCO₂e.p⁻¹.yr⁻¹ for LEGOS and LAERO respectively. Importantly, the total emissions are
510 strongly correlated to the total financial budget of the laboratory (R=0.96) with a mean footprint
511 of 388 +/- 72 tCO₂e.M€⁻¹ spent (excluding travel expenses) and the budget itself is strongly
512 correlated to the staff size (R=0.80) with typically about 10 k€.yr⁻¹ spent per agent, with the
513 LEFE and IRAP at the lower and upper end of the spectrum with 4.4 k€.yr⁻¹ and 13.9 k€.yr⁻¹,
514 respectively.

516 Beyond IT equipment of the laboratories, the use of external IT infrastructure also represent a
517 minor increase of the footprint, about 0.1 to 0.5 tCO₂.p⁻¹.yr⁻¹. This value, however, is uncertain
518 because of its reliance of a poll with a limited response level, except in LAERO where most
519 researchers relying on external IT where individually asked about their practice.

520

521 3.3 Carbon footprint of professional travels

522 Professional travels also represent a major share (in the top 3 for all laboratories) of the CF, with
523 a mean of 3 tCO₂e.p⁻¹.yr⁻¹ (Figure 2). In all cases air-travel represents more than 80-90% of the
524 total travel emissions, consistent with the fact it also represents more than 70-80% of the
525 distance traveled. As a result the total traveled distance is strongly correlated with the total
526 footprint (Table 1). The spread in emissions and traveled distances seems related to the structure
527 and focus of the laboratories. At the upper end with 6.1 tCO₂e.p⁻¹.yr⁻¹ the LEGOS has many
528 researchers funded by the IRD, an institute with a research focused on collaboration with the
529 Global South countries, and thus often distant field areas. At the lower end with 1.3
530 tCO₂e.p⁻¹.yr⁻¹, the LEFE has most of its researchers with teaching duties and most of its research
531 field areas in Southwest France and the Pyrenees.

532 Turning to daily commuting to reach the laboratories, we estimate that it represents between 0.3
533 and 0.8 tCO₂e.p⁻¹.yr⁻¹, thus a modest share between 3 and 12% of the total CF. The studied
534 laboratories often have nearly 50% of the total commuting distance traveled by bicycle, train or
535 public transport with very low emissions, while the rest is mostly traveled by car which dominate
536 the emissions.

537 We also note that even if it may be somewhat overestimated, the CF for hotel nights are
538 substantial from 0.3 to 1 tCO₂e.p⁻¹.yr⁻¹, which is superior to commuting emissions for 4 out of 6
539 laboratories.

540

541 3.4 Carbon footprint of laboratory in-situ operations

542 Last, we find that the general operations of the building hosting the equipment and staff of the
543 laboratory always represent a minor share of the footprint. Electricity consumption represents
544 between 0.1 and 0.5 tCO₂e.p⁻¹.yr⁻¹, while the heating footprint is between 0.3 and 1 tCO₂e.p⁻¹.yr⁻¹,
545 except for the CESBIO which benefits from a heating system based on biomass and thus
546 has a much lower footprint of 0.05 tCO₂e.p⁻¹.yr⁻¹. Refrigerant fluids used by some labs in
547 cooling systems add 0.01 to 0.3 tCO₂e.p⁻¹.yr⁻¹. The footprint of water consumption is estimated
548 at less than 0.01 tCO₂e/p for all laboratories, thus excluded from figures for simplicity, while
549 waste disposal is estimated to represent between 0.03 and 0.2 tCO₂e.p⁻¹.yr⁻¹. In contrast, meals
550 taken at the workplace are representing a larger footprint between 0.23 and 0.45 tCO₂e.p⁻¹.yr⁻¹,
551 the spread reflecting the diversity of diet habits. Summing all these items yield a footprint of 0.8
552 and 1.9 tCO₂e.p⁻¹.yr⁻¹, typically representing between 5 and 20% of the total footprint (Figure 2)
553 except for the CESBIO with a smaller footprint due to its decarbonized heating, and because
554 waste and meals data were not retrieved for this laboratory.

555

556 4 Discussion

557 Our key result is that a comprehensive scope yields large footprints above 10 tCO₂e.p⁻¹.yr⁻¹, for
558 most Earth, Environmental and Space Science labs, and that a substantial if not dominant part of
559 this footprint is related to research infrastructures, in particular satellites. We thus start this
560 discussion by comparing these footprints to other recent works on the footprint of scientific
561 institutions, and discussing the various uncertainties that affect them. We then briefly discuss
562 reasons for the Earth scientists to be particularly pro-active in reducing their annual footprint
563 before quantifying some classical reduction measures and their limits and ending on less
564 quantitative propositions that rather advocate rethinking how and why we produce knowledge.

565 4.1 General estimates, comparison to recent work, and major uncertainties

566 The carbon footprints we report are significantly above many previous estimates for European
567 institutions. Still, excluding research infrastructures, rarely examined in the literature until now,
568 they are in the range of other European universities or research institutes (about 10 tCO₂e.p⁻¹

569 ¹.yr⁻¹, ALLEA, 2022) and other French laboratories both in terms of travels (1-3 tCO₂e.p⁻¹.yr⁻¹)
570 and expenses (2-4 tCO₂e.p⁻¹.yr⁻¹) (See Mariette et al. 2022, De Paepe et al., 2023). We note that
571 our estimate of carbon intensity for purchases, 388 +/- 72 tCO₂e.M€⁻¹, is about 20% higher than
572 the estimate of De Paepe et al., (2023) for 108 French science and technology labs, at 320 +/-
573 100 tCO₂e.M€⁻¹. Thus, we consider that our crude approach yields close enough results and that
574 their more robust methodology, that we recommend for future work, would not affect our
575 conclusions. Yet, this difference shows some uncertainty associated to the use of EF from a
576 national database with limited and generic EF classes. Besides, this financial approaches that
577 links prices and GHG emissions is very dependent on the time when these factors have been
578 computed, and year-to-year comparison should acknowledge potential inflation.

579 The total footprint with extended scope (including satellites but no other research infrastructures
580 based on ships, aircrafts or ground infrastructures) we have obtained a range from 5 to 30
581 tCO₂e.p⁻¹, and above 15 tCO₂e.p⁻¹ for the three laboratories with substantial contribution from
582 satellite infrastructure. For the estimated footprint of Earth Observation satellite we identify
583 several dominant sources of uncertainties that should be addressed in future works. First, as
584 identified by Knödlseeder et al., (2022), the uncertainties on the emission factor (50 tCO₂e.kg⁻¹ or
585 1450 kgCO₂e.M€⁻¹) remain high, and we urge actors from the space sector to release and
586 publish additional estimates for various satellite missions. At this stage we have no way to
587 differentiate the footprint of a new versus a follow-up mission, or a mission made of many small
588 satellites (e.g., cubesats or nanosats) versus one large satellite of identical weight. Another issue
589 is the time over which the footprint is distributed in order to, in a sense, amortize the footprint
590 over a certain duration and derive an annual footprint. Especially the minimal write-off time was
591 set to 10 years to be comparable to Knödlseeder et al., 2022. Doubling this minimal time of
592 amortization would reduce the footprint by about by 15% for most laboratories, 20% for the
593 GET and 25% for the CESBIO, but leave satellite as a top source of CO₂ in the laboratory
594 heavily using them.

595 Another major uncertainty is on *S_s*, the share to science. Indeed, many satellites used by Earth
596 scientists have mixed applications (military, meteorological, industrial ...) and we could find no
597 specific way to estimate the share of usage of each application. We have assumed a typical value
598 of *S_s*=0.4 based on user reports of the Copernicus Sentinel satellites and applied this for 11
599 missions. If those missions had *S_s*=0.2 or *S_s*=0.6 the satellite footprint would only change by +/-
600 5% for GET, LEGOS, and LAERO reflecting the fact that many of the satellite they use are more
601 specialized (e.g., for gravimetry, ocean waves or atmospheric chemistry). In contrast the
602 uncertainty would reach 15% and 20% for the CESBIO and LEFE, respectively. Consistently,
603 setting *S_s*=0 would reduce even more the total satellite footprint by about 10% for GET and

604 LEGOS, 15% for LAERO, 30% for CESBIO and 40% for LEFE. Last, if we assume that even
605 for specialized missions some public or commercial use exist, and thus set $S_s=0.4$ for the same
606 11 missions and $S_s=0.6$ for all the others, this would reduce the satellite footprint by 30-35% for
607 most laboratories (Table S3). Nevertheless, although there is clearly room for improving the
608 estimation of the footprint of satellites, we consider that their order of magnitude will not change
609 and therefore will remain a substantial or even dominant part of the budget for the studied
610 laboratories.

611

612 Attempting to constrain the footprint of other research infrastructures taking parts in various
613 Earth and Space science laboratory is even more challenging, given their diversity in size and
614 nature. Collecting and aggregating data to derive the footprint of more research infrastructures
615 remains a challenge for the scientific communities, with important pioneering examples from
616 astrophysics (Aujoux et al., 2021, Knödlseeder, et al., 2022), meteorology (Stevens et al., 2021),
617 or particle physics (Bloom et al., 2022). Still, the example of IRAP shows that ground
618 infrastructures may be far from negligible and actually represent another dominant part of the
619 budget (Fig 2 and Martin et al., 2022a). The footprint of other infrastructures are smaller, and
620 can range from small (IODP) to moderate (IAGOS) when attributed to a given laboratory. Still,
621 we encourage more efforts in assessing this contribution for several reasons. First, infrastructures
622 not yet assessed may increase substantially the global footprint of laboratories, as it was the case
623 for IRAP. Second, including infrastructures may allow to correctly attribute emissions, and
624 associated responsibilities, and may remove some sources from a given lab and redistribute it
625 globally. For example air-travels to reach an IODP oceanographic cruise, as well as days at sea,
626 should not be entirely attributed to the footprint of the laboratory. Of even larger impact, an
627 oceanographic cruise dedicated to a given laboratory may emit up to $1.6 \text{ tCO}_2\text{e}\cdot\text{d}^{-1}\cdot\text{p}^{-1}$ (See SI)
628 and weight heavily in one lab's budget. For the GET the direct and entire attribution of all days
629 at sea would represent $672 \text{ tCO}_2\text{e}$, more than 20 times the $25 \text{ tCO}_2\text{e}$ we obtain when distributing
630 the footprint over the international user community. This may also be true for instruments
631 acquired by a laboratory but actually deployed within an observatory. We could not trace in
632 details such practices although several laboratories are taking part or even coordinating such
633 international observatories, such as HYBAM or M-TROPICS, for the GET, and OSR-SO for the
634 CESBIO. Still a preliminary observation for the CESBIO was that at least $63 \text{ tCO}_2\text{e}$ were
635 associated with OSR-SO maintenance in 2019, among which $44 \text{ tCO}_2\text{e}$ of equipment purchases,
636 which represent 13% of the CESBIO non-IT purchases. Depending on the usage of the CESBIO
637 of the data produced by this observatory, and on the contribution of other laboratories to OSR-
638 SO, the global footprint of the CESBIO could actually be reduced. In contrast attributing to the

639 CESBIO its share of footprint associated to observatories managed by other laboratories would
640 increase its footprint. For now, it is unclear whether attributing properly the footprint of these
641 medium scale infrastructures will increase or decrease significantly the budget of the studied
642 laboratories.

643

644 In any case, our study highlights that it is absolutely necessary to include Scope 3 emissions, and
645 more specifically, we insist on not only focusing on air-travels but also on purchases and
646 research infrastructures.

647

648 4.2 Typical reduction measures and their quantitative impact

649 The comprehensive CF we presented allow us to estimate the effects of typical measures aiming
650 at reducing them. Given the diversity of size and practice of the studied laboratories, we present
651 the relative effect of these measures, although their effect in terms of tCO₂e saved may be quite
652 variable. Importantly we give the average effects for these measures for laboratories with
653 substantial infrastructure footprint and for the two laboratories where the infrastructures are a
654 small part of the budget (LEFE and LAERO).

655 First we start with commonly discussed measures, relating to building efficiency or
656 environmentally friendly daily practice such as diets and commuting habits. Measures allowing
657 to reduce by 50% electricity and heating, as prescribed by the national strategy to reduce carbon
658 emissions, would typically yield global reduction of 1 to 3% and up to 4 and 7% for the LAERO
659 and LEFE. Measures increasing carpooling and modal report to bike and public transport would
660 represent a drop by only 0.5-2% of the global footprint if they achieve a reduction by 50% of the
661 commuting distances traveled by cars, but up to 3 and 6% for the LAERO and LEFE. A similar
662 reduction of 0.5-2%, would be obtained if halving the footprint of lunch meals, for example by
663 contracting the food provider to serve more vegetarian diet and ban beef. Measures targeting
664 waste or water would have even less impact on the CF. Thus, achieving all these measures that
665 certainly require substantial efforts, would only have a limited impact, which even for the LEFE
666 would remain about 15%.

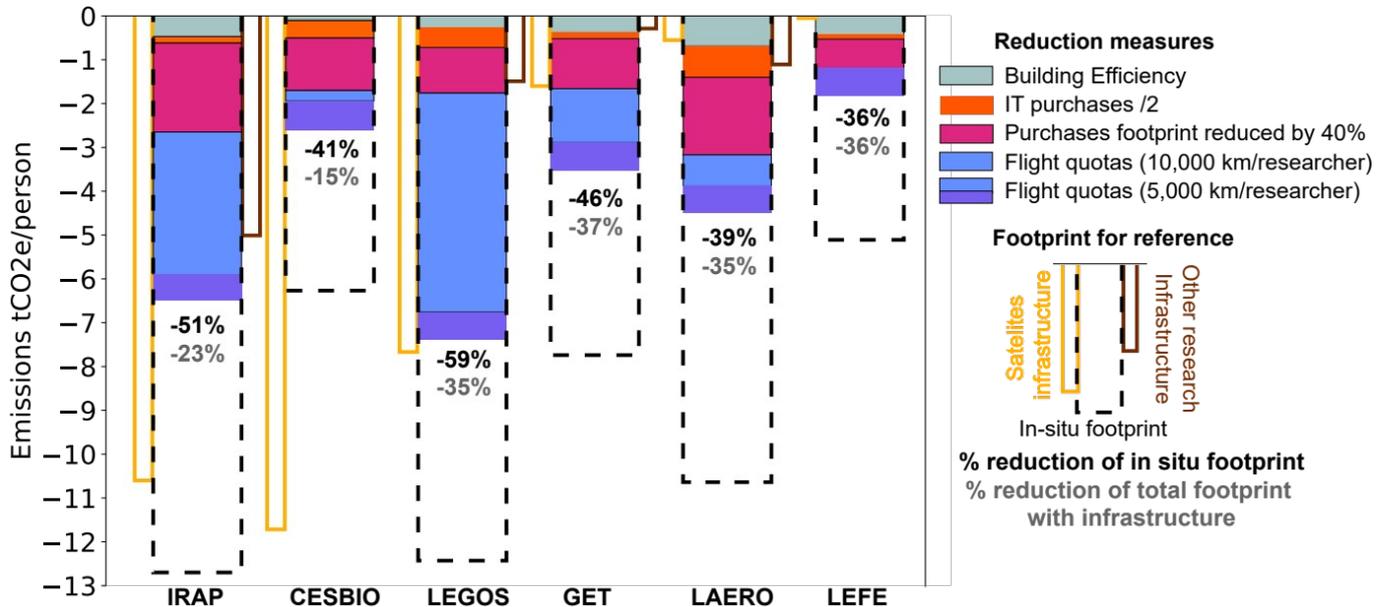
667 Turning to measures that would affect more directly scientific practices but could probably be
668 achieved with a limited impact on scientific output, we could envision measures affecting
669 mobility and equipment. For example imposing train travel within metropolitan France would
670 reduce the total footprint by 2-3%. More substantial reductions could be achieved by targeting
671 long distance flights and frequent travelers. Indeed, the distribution of flights is often very
672 unequal with few individuals representing a large share of the air-travel footprint (Martin et al.,

2022a, Berné et al., 2022, Ben-Ari et al., 2023). Thus, flight quotas, which are already experimented by some pioneer laboratories in France (IGE, IRIT, LOCEAN), could be a high-impact measure leading to a reduction of up to 20-60% of the travel footprint (Ben-Ari et al., 2023). Various implementation of quotas are possible (e.g. by research team, reportable over 2 or 3 years, accounting for career stage) but for a first-order estimate, we consider a flight quota of 10,000 km.p⁻¹.yr⁻¹, attributed to each non-support staff (typically 60-70% of the total staff, Table 1). Assuming full usage and an average emission factor between medium-haul and long-haul flights (i.e., 0.17 kgCO₂e.km⁻¹ as in Ben-Ari et al., 2023), we obtain a footprint equivalent to a reduction varying between 0% (LEFE) to 80% (LEGOS) of the 2019 travel footprint, which means 0% to 23% of reduction of the comprehensive footprint (Figure 4). Note that these numbers would increase by a few percents if we consider a stricter limit of 5,000 km per year or if we consider only 50% of the quotas would be used. For IRAP and LEGOS, this is clearly one of the most impacting measure, but with effects hard to predict on how we practice science. Indeed, video conferencing is popular and becomes more common as a replacement for flying to attend meetings or jurys, or to collaborate with distant colleagues. It is also often put forward as a solution in serious games (Gratiot et al., 2023). Still, visibility and thus career may be correlated to flying (Berné et al., 2023), even if others argued against such link (Wynes et al., 2019), and if such correlation may reflect previous practices that have rapidly evolved since the Covid crisis. In any case, beyond scientific visibility, data collection through fieldwork alone may consume a large part of quotas in some Earth, Environmental, and Space science laboratories, such as GET where missions labeled as fieldwork represent 40% of the overall mission footprint, much more than the average of other French laboratories (~7%, Ben-Ari et al., 2023). The impact on inclusion of researchers with a disability, or family constraints, may also be a source of tension when attempting to organize modal report, but some hybrid or virtual meetings may actually be more inclusive.

In terms of expenses, a detailed analysis of the impact of seven measures to reduce expenses over a database of French laboratories was performed by De Paepe et al. (2023). Most measures focused on reducing purchases by extending lifetime, or pooling equipment, or avoiding disposable devices. For life and health science, and science and technology such measures could reduce the footprint of expenses by up to 40% (De Paepe et al., 2023), which depending on the lab would mean a reduction of 7 to 13% and up to 20 and 17% for the LAERO and LEFE (Figure 4). The single measure of halving IT Purchases by extending their lifetime (if needed by paying extra warranty) represents a reduction of 2% for several labs and 6% for the LAERO. Again the impact of these measures on scientific productivity or labs' financial budget is unclear. Extra work is associated with replacing plastic by glass, which involves cleaning, or pooling lab

708 equipment, which requires additional organization among various labs. Financial rules
 709 concerning warranties and second-hand purchases may also need to be adapted.
 710 Whatever the associated impacts, if all these measures would be applied, they would achieve 15-
 711 20 % reduction for labs relying most on research infrastructure (CESBIO and IRAP) and about
 712 35% for other labs (Figure 4).

713



715 **Figure 4:** Reduction of the footprint achievable through a set of measures (halving building
 716 electricity and heating; halving IT purchases; 40% reduction of the purchases footprint
 717 following the measures of De Paepe et al., 2023; and flight quotas), compared to the current total
 718 in-situ footprint (dashed) and the research infrastructure footprints for each laboratory. The
 719 numbers indicate the total achievable reductions in % of the in-situ (black) and total (= in situ +
 720 infrastructures, grey) footprints.

721

722 The large share of research infrastructures is strictly capping the potential of reduction (in
 723 relative value), and we underlined that the scope of considered infrastructures for various labs
 724 may be underestimated. In absolute terms, satellite infrastructures represent several $\text{tCO}_2\text{e.p}^{-1}.\text{yr}^{-1}$
 725 and about $10 \text{ tCO}_2\text{e.p}^{-1}.\text{yr}^{-1}$ for several labs. Reducing substantially the footprint of large research
 726 infrastructures cannot be limited to decarbonizing the existing ones, but also likely requires a
 727 reduction of the frequency and/or size of the newly deployed infrastructures (Knödlseeder et al.,
 728 2022), informed by environmental life-cycle assessments (e.g., Janot and Blondel, 2023). Given
 729 that research infrastructures are by definition objects shared and managed by large communities,
 730 often international consortia, the challenge of defining a sustainable strategy for research

731 infrastructures is by essence collective and political, and thus is beyond the hands of any single
732 scientist or laboratory. Thus, the implication of international scientific institutions such as the
733 American Geophysical Union or the European Geoscience Union could be essential to weigh in
734 negotiations about the future of scientific infrastructures.

735

736 4.3 Other avenues to limit the carbon footprint of laboratories and research infrastructures

737 Here we discuss structural changes in the organization of scientific activity that may allow more
738 substantial reduction of laboratories footprint and facilitate the implementation of measures
739 presented above. In recent decades, scientific activity has been organized under the ideal of
740 excellence, where funding is conditioned to the results of an intensive competition, at national
741 and international scale. Recurrent funding is thus limited and scientists are pushed to compete
742 with promises of breakthrough, backed by cutting-edge technologies and infrastructures. In this
743 “fast-science” competition, the credibility of scientists and institutes is mostly assessed with
744 publication indicators, as well as their ability to capture new research credits. Below, we briefly
745 outline how turning away from this model, could allow to reduce the ecological footprint of
746 laboratories, among other changes.

747 First, in order to publish new results at an ever faster rate, as seen from an exponentially
748 growing number of publications over the last decades (e.g., Bornmann and Mutz, 2015),
749 scientists devote substantial amount of resources to acquire, analyze and interpret data. Given the
750 significant correlation between laboratory financial budget and purchase CF (Table 1, De Paepe
751 et al., 2023), a relationship which probably also holds in the case of travel CF, we posit that the
752 growing trend in publications is closely associated with the GHG footprint of scientific research.
753 However, this growth of publication is correlated to a decline in disruptive publications and
754 patents, even for the most renowned journal (Park et al., 2023), signing increasing level of waste
755 - not to mention potential influence on the occurrence of scientific misconducts (Gross, 2016,
756 Roy and Edwards, 2023). Thus, rethinking scientific institutions toward the framework of “slow-
757 science”, i.e., “doing less but better” (Stengers, 2018, Frith, 2020, Urai and Kelly, 2023) could
758 preserve scientific knowledge production while reducing laboratories CF, with likely co-benefits
759 in terms of working conditions and health (e.g., Hall, 2023).

760 Second, promoting and organizing collaboration rather than competition would facilitate the
761 pooling of equipment and infrastructures (at various scales) rather than their duplication, and
762 reduce the need for long-distance travel to acquire new data by using instead a fair network of
763 collaboration with international colleagues, both allowing to reduce major sources of GHG
764 emissions. Recurrent collective funding instead of episodic individual funding through grants,

765 could allow to avoid the incentive to “use up” remaining funding (at the end of the year or of the
766 project) into equipment. More indirectly it could favor work focusing on analyzing and
767 interpreting archived data rather than work pushing for novel data acquisition through large
768 grants, which is rarely fully exploited.

769 Last, promoting broader recognition of the role of scientists within society (actionable and
770 socially-relevant science) rather than only focusing on innovation and mere knowledge
771 production, could also allow scientists to spend more time on academic activities that can be
772 achieved locally, with low-tech equipment and/or no or reduced research infrastructures. Such
773 activities could include research-actions or participatory-science (see Lee et al., 2020),
774 developing collaboration with policy centers, or ethics-driven engagement in various ways with
775 diverse types of public to promote systemic understanding of the ongoing crisis and its link with
776 social, political and economic institutions (see Fragnière, 2022, Gardner et al., 2021). This last
777 proposition is important as greater scientific engagement is expected by the public (e.g., on
778 issues related to climate change, Cologna et al., 2021), does not compromise scientific credibility
779 (Kotcher et al., 2017), while it could contribute to more rapid mobilization and adoption of
780 political measures to address the climate and biodiversity emergencies (Gardner et al., 2021,
781 Capstick et al., 2022). Another general direction includes reflexive approaches of (geo)sciences
782 in which we analyze our own scientific activity, frequently with an interdisciplinary approach
783 including social sciences, trying to address interconnected questions such as how, why and for
784 whom we work, and with which consequences (see recent examples in geoscience, Stewart and
785 Hurth 2020, Reimer et al., 2021). In practice, these activities could be promoted by being
786 explicitly valued within guidelines of academic juries (for recruitment or promotion).

788 **5 Conclusion**

789 We have presented a comprehensive estimate of the green-house gas footprint of six laboratories
790 from the Earth, Environment and Space Sciences (EESS). The main novelty of these budgets is
791 that the scope 3 also includes research infrastructures, and notably satellite infrastructures. We
792 have generalized the methodology of Knödlseeder et al., (2022), to attribute a meaningful fraction
793 of the footprint of research infrastructures to research laboratories. This fraction is obtained by
794 counting the affiliated authors among publications associated with the infrastructures, retrieved
795 from the global Web of Science database. The method is applied to 44 satellite missions used by
796 geoscientists as well to 3 other international infrastructures relying on ships or planes.
797 Consistently with Knödlseeder et al., (2022), we found that altogether, satellite infrastructures is a
798 dominant share of the budget for three laboratories, between 40 and 65%, reaching 7 to 11

799 tCO₂e.p⁻¹. Other type of research infrastructures were only partially assessed, but represented up
800 to 1.5 tCO₂e.p⁻¹, and a comprehensive integration of all research infrastructures into the GHG
801 footprint of laboratories remains a challenge for future research. Together with infrastructures,
802 air travels and purchases (mostly of scientific and IT equipment) represent other major shares of
803 the budget, typically between 2-4 tCO₂e.p⁻¹ for each source, and bring the annual footprint above
804 10 tCO₂e.p⁻¹ for five out of six laboratories. As a consequence, radical footprint reduction
805 strategies, based on flight quotas and diverse reductions of purchased equipment may reach
806 reductions between 40% and 60% of the in-situ laboratory footprint, but is limited to reduction
807 of 15 - 30% of the total footprint for the laboratories heavily using research infrastructures. We
808 finally suggest that a deep reorganization of scientific activity away from a competitive fast-
809 science ideal may be an essential step for more sustainable scientific practice.

810 To remain exemplary and thus contribute to political actions towards addressing ecological
811 emergencies (Attari et al., 2016, 2019, Gardner et al., 2021), we urge the EESS community, to
812 publicly engage into quantitative plans for ecological footprint reduction. For example,
813 laboratories, departments, or institutes could commit into targets consistent with the 6th IPCC
814 report (IPCC, 2022) with a reduction target of about 45% of their 2019 in-situ footprint achieved
815 by 2030, and continued reduction beyond this date, as already pioneered by some laboratories
816 (e.g., Pellarin et al., 2023). In parallel, we call on collective discussion across the EESS
817 community, including large organization such as AGU and EGU, funding agencies, and space
818 agencies, toward a rethinking the deployment of new infrastructure. Indeed, a reduction of the
819 size and deployment frequency of new research infrastructures is probably the only way to
820 reduce the overall environmental footprint of scientific institutions. We believe that, these two
821 specific goals, rather than seen as a sanction or constraints, should be embraced as stimulating,
822 long-term challenge for the emergence of a more sustainable, meaningful and healthier scientific
823 practice, at the individual and collective scale (Hall, 2023, Urai and Kelly, 2023).

824

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844 **Open Research**

845 Data relevant to the carbon footprint of IRAP is available from Martin et al., 2022b. Data
846 concerning emission factors is publicly available from UK Government (2020) and ADEME
847 (2023). Data concerning activity and publications for the IAGOS, PIRATA and IODP
848 infrastructures is publicly available online at AGI and IODP, (2024), IAGOS, (2024), IODP
849 (2024), NOAA, (2024) and PIRATA (2024). Other estimates of carbon footprint derived from
850 laboratory activity data and infrastructure data are available through the Supplementary Table 2
851 to 4 which are available online at <https://doi.org/10.5281/zenodo.10776609>. Data concerning
852 satellite missions characteristics is available from online as summarized in Table S3.

853 To estimate the carbon footprint associated with travels we used the GES1.5
854 (<https://apps.labos1point5.org/ges-1point5>) online tool developed by Labos1.5
855 (<https://labos1point5.org/>).

856

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