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RESEARCH ARTICLE

Comprehensive carbon footprint of Earth, environmental and space science laboratories: Implications for sustainable scientific practice

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Abstract

To limit global warming below 2˚C, a drastic overall reduction from current green-house gas emissions is needed. Scientists should also participate in this effort in their professional activity and especially Earth scientists, on the grounds of maintaining credibility and leading by example. The strategies and measures to reach a low-carbon scientific activity require detailed estimates of the current footprint of laboratories. Here, we present the footprint of six laboratories in Earth, environmental and space sciences, with a comprehensive scope also including international research infrastructures. We propose a novel method to attribute a part of the footprint of any research infrastructure to the laboratory using it. Our results highlight that most laboratories have annual footprints reaching 10–20 tonnes CO_2equivalent per person (tCO2e p^{-1}), dominated by infrastructures and specifically satellites in three cases (with footprints up to 11 tCO2e p^{-1}), while air-travels and purchases remain within the top three sources in all cases (2–4 tCO2e p^{-1} each). Consequently, footprints related to commuting and laboratory functioning, about 2 tCO2e p^{-1} or less, are relatively modest compared to infrastructures, purchases and air-travels. Thus, reduction measures ignoring infrastructures may not be able to achieve reductions larger than 20 to 35% even with flight quotas and a substantial reduction of purchases. Finally, we also discuss how a deeper transformation of scientific practices, away from competitive, grant-based and innovation-oriented current practices, could make Earth and environmental sciences more sustainable and at the forefront of rapid and drastic changes in the whole society toward environment and climate preservation.

et al., 2022b. Data concerning emission factors is publicly available from UK Government (2020) and ADEME (2023). Data concerning activity and publications for the IAGOS, PIRATA and IODP infrastructures is publicly available online at AGI and IODP, (2024), IAGOS, (2024), IODP (2024), NOAA, (2024) and PIRATA (2024). Data concerning satellite missions characteristics is available from online as summarized in S3 Table. Other estimates of carbon footprint derived from laboratory aggregated activity data and infrastructure data are available through the Supplementary Table 2 to 4 which are available online at https://zenodo.org/records/13928353. However, detailed financial listings of purchased or travel listings are not provided due to legal restrictions. These listings disclose the financial and travel data of the studied research laboratories and belong to the laboratories' institutions which establish the secret of financial and economic information (for more information, please contact dgdr.secretariat@cnrs.fr). To estimate the carbon footprint associated with travels we used the GES1.5 (https://apps.labos1point5.org/ges-1point5) online tool developed by Labos1.5 (https://labos1point5.org/).

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Author summary

To limit global warming below 2˚C, a drastic overall reduction from current greenhouse gas emissions is needed. We argue that scientists should also participate in this effort in their professional activity and especially Earth scientists, on the grounds of maintaining credibility and leading by example. Here, we present the footprint of six laboratories in Earth, environmental and space sciences, with a comprehensive scope also including international research infrastructures. With a novel method to attribute a part of the footprint of a research infrastructure to the research laboratories using this infrastructure, we find that most laboratories have annual footprints reaching 10–20 tonnes CO_2 equivalent per person, dominated by infrastructures and satellites in three cases, while air-travels and equipment purchases remain within the top three sources in all cases. In comparison, footprints related to commuting and laboratory functioning, are relatively modest. Thus, reduction measures ignoring infrastructures may not be able to achieve reductions larger than 20 to 35% even with flight quotas and a substantial reduction of purchases. Finally, we also discuss how a deeper transformation of scientific practices could make Earth and environmental sciences more sustainable and at the forefront of a rapid and drastic changes in the whole society toward environment and climate preservation.

1. Introduction

The sixth series of IPCC assessment reports underlined the need for an immediate and rapid decay of greenhouse gases (GHG) emissions to mitigate current warming pathways and associated cascading impacts [1]. Maintaining global warming below 2˚C (in 2100) implies reducing GHG emissions by ca 25% and 60% by 2030 and 2050, respectively, reaching an average of emissions per capita ca 2 $tCO_2e\ p^{-1}\ yr^{-1}$ on Earth in 2050 (see Fig TS.9 of [1]). Although responsibilities vary, it is clear that substantial reductions must affect all aspects of society, including academia.

Although various discourses of inaction [2] are also present inside scientific laboratories [3], several lines of argument indicate that academia has a specific responsibility to be exemplary in terms of reducing its GHG footprint. First, various studies, including IPCC assessment reports, highlight that the political feasibility of a rapid decarbonization of society likely requires various forms of social justice and reduction of inequalities [1,4,5]. It means that privileged actors, including the academic sector, are arguably among those compelled to reduce first and/or at an accelerated pace their GHG emissions.

Then, beyond their moral responsibility [6], the credibility and status of the Earth and environmental science community, broadly working on ecological issues, is linked to adopting exemplary professional practices and personal lifestyles. Surveys showed for instance that GHG mitigation policies proposed by climate researchers tended to be more or less supported by the public depending on the reported carbon footprints of their proponent (low or high, respectively [7,8]). This emphasizes the importance for geoscientists to be leader in terms of reducing their own GHG footprint.

Efforts towards exemplary practices require a comprehensive assessment of environmental impacts of academia, and an effort in building transparent and reproducible methods. Focusing on GHG, the carbon footprint (CF) measures all direct and indirect GHG emissions (converted to CO_2-equivalent emissions, CO_2e), more specifically in scope 1 (direct process emissions), scope 2 (indirect emissions arising from energy purchase) and scope 3 (all other indirect emissions including the purchase of goods and services) according to the GHG protocol [9]. Methodologies to determine CF have been existing for several decades and applied to various entities and at various scales [10,11], including academic institutions such as research institutes or universities. However, most studies on academic CF used limited scopes with a restricted scope 3 focused on mobility. Thus, they have reported air-travel to be the largest source, with several $tCO_2e\ p^{-1}$ [12–15], while being very unequally distributed [16–18]. Many studies pointed out the potential of CF reduction through low-carbon alternatives (eg., train travel, video call, reorganizing conferences, [18–20]).

Nevertheless, beyond mobility, there were various attempts to quantify the carbon footprint of other aspects of academia, such as that of product and service consumption [e.g., 21,22]. Studies assessing the CF of purchases for a Norwegian university [23] or more recently for >100 French research units [24,25], found them to represent 30 to 50% of the total CF, and several European universities have estimated their total per employee CF between 10 and 30 $tCO_2e\ p^{-1}$ when including purchases [26].

More recently, CF estimates for large/international research infrastructures have also been released, including satellite and ground telescopes for astronomy [27], the GRAND astrophysics project [28] or the infrastructures used for particle physics such as the CERN (European Center for Nuclear Research, [29,30]). These CF estimates often relied heavily on scope 3 emissions, which could represent a very large share of the annual CF of research institutes when infrastructure use is included in the laboratory footprint. Indeed, with a comprehensive inventory of emissions, the largest French research institute in astronomy and astrophysics (IRAP) found that the contribution of using satellite and ground observatories amounted to 38% and 18% of its CF in 2019, while air-travels and purchases represented lower contributions with 16% and 18%, respectively [31]. The magnitude of the CF, nearing 30 $tCO_2e\ p^{-1}\ yr^{-1}$ for the 263 employees of this laboratory, made [31] recommend urgent substantial reorganization of research practices and goals in astronomy and astrophysics.

Compared to many other natural and physical sciences, Earth, environmental and space sciences (EESS) study processes over a variety of temporal and spatial scales that may be difficult to replicate in the lab or to study in a single field area. As a result, for many individual researcher as well as whole community (e.g., Oceanographers), they rely on complex international infrastructures, such as satellites, networks of monitoring systems or research vessels, providing unique observations, in their nature and/or in their spatio-temporal coverage. Further, in contrast to space sciences, Earth and environmental sciences use infrastructures which are more diverse in nature but also have larger community of users, including non-scientific actors, requiring to adapt and update the method proposed by [27]. As a result, such a comprehensive inventory of emissions, including the use of research infrastructures, remain missing for laboratories in Earth and environmental sciences, limiting our ability to propose sustainable trajectories for these fields.

To address these research challenges, we present an updated method to attribute the use of research infrastructures to research laboratory. We apply it to six research laboratories which formed the Observatoire Midi-Pyrénées in 2019, a large French public research institute of EESS, allowing for the first time to reveal the dominant share of the CF that could arise from intensive use of research infrastructure and specifically Earth observation satellites in those disciplines, and to discuss the implications in terms of reduction strategy.

Table 1. Summary of activities and key sources of CO2 emissions for the six laboratories affiliated to the OMP in 2019 with all info for IRAP (except Publications) from [31]. Purchase budgets are excluding expenses for professional travels and administrative transfers. Abbreviations as following, IT = Information Technology, RI = Research Infrastructure, Sat = Satellites, Obs = ground astronomical observatories, Air = IAGOS infrastructure, Sea = IODP (for GET) and PIRATA (for LEGOS) infrastructure and use of other large research ships.

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
Publications 2015–2019 (yr^{-1} p^{-1})	1,11	1,32	1,26	0,75	0,94	1,21
Considered Infrastructures	Sat	Sat + Sea	Sat + Obs	Sat + Air	Sat	Sat + Sea
Professional travels, in 10^3km p^{-1}	6.4	15.7	24.3	11.1	6.4	39.7
Purchase budget, in 10^3€ p^{-1}	6.4	5.2	14.1	12.4	3.7	7.1
Travels (tCO_2e p^{-1})	1.5	2.5	4.5	1.9	1.3	6.1
Purchases (with IT) (tCO_2e p^{-1})	2.3	2.5	5.4	5.7	1.7	2.9
Total in-situ (tCO_2e p^{-1})	6.2	7.2	12.6	11.3	5.5	11.5
Total with RI (tCO_2e p^{-1})	17.8	9.2	28.2	13.14	5.5	20.8

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2. Data and Methods

2.1. Presentation of the studied laboratories

Staff and activity data of the six laboratories composing the Observatoire Midi-Pyrénées (OMP, www.omp.eu) in 2019 are summarized in Table 1. Here, we briefly describe their scientific focus. The CESBIO (Centre d'Etude Spatiale de la BIOsphere) focuses on continental surfaces and more specifically on soil/vegetation/atmosphere interactions, with a strong expertise in remote sensing data. The GET (Géosciences Environnement Toulouse) is a laboratory with prime expertise in geology, geophysics, geochemistry, hydrology and environmental processes. The IRAP (Institut de Recherche en Astrophysique et Planetologie) has broad expertise in observing, modeling and instrumenting all aspects of astrophysics and planetology. The LAERO (Laboratoire d'Aérologie) focuses on the physics and chemistry of the lower atmosphere through observation and numerical modeling. The LEFE (Laboratoire Ecologie Fonctionnelle et d'Environnement, which has merged with another unit in 2023) focuses on ecosystem health, ecosystem services and ecological responses to global changes. The LEGOS (Laboratoire d'Etude en Géophysique et Océanographie Spatiales) focuses on the water cycle in the broadest sense, with the physics of the oceanic, hydrological, cryospheric and atmospheric components, including coastal and climatic components, as well as marine biogeochemistry and geochemistry.

For each laboratory, we only consider persons with continuous contracts over the whole year 2019, including PhD and postdoctoral researchers, administrative and technical support staff (up to research engineers), and permanent research and teaching staff. We recall that all results from IRAP have been published in [17,31], following [27] for research infrastructures, and their figures are reported for comparison with the other laboratories of the OMP to have a broad discussion about Earth, environmental and space Sciences.

2.2. GHG budget method and scope

To assess GHG emissions, we followed standard procedure in which 'activity data' that quantify the usage of a given source (e.g., energy consumption in kilowatt hours, or travel distances in kilometers, etc.) are multiplied by associated 'emission factors' (EF) that quantify the unitary carbon footprint of each source (Table 1, S1 Table). To constrain the emissions of commuting, electricity, gas, cooling fluids, and professional travels we followed the standardized approach proposed by [15], and used the GES1.5 tool. For air-travels, we present results including the indirect radiative forcing of condensation trails, which are equivalent to doubling the footprint derived from CO_2 only [15].

Additionally, the emissions related to expenses (i.e., the GHG emissions resulting from the life-cycle of products or services bought by the laboratory) are considered by listing financial costs, for which EF, in $kgCO_2e$ $k€^{-1}$, are attributed to different categories of good and services, such as edition, clothes, furniture, electronics, machines, etc. [21,22,24](S1 Text).

Following [17,31], the scope of our assessment was extended to more items (S2 Table). Emissions of (i) external data storage and computation, and (ii) food consumed were assessed with online polls, to constrain annual activity in each laboratory in terms of (i) CPU.hour, terabytes (TB) and (ii) number of meals of various diets. Most external computing is performed in France and thus a relevant EF of 3.6 gCO_2e (CPU hour)$^{-1}$ is used [32]. One TB of data stored for a year in a datacenter, represents an EF of 12 $kgCO_2e$ in France. The median value for other countries, with less favorable electricity mix, is rather 35 $kgCO_2e$ [33]. As the location of the datacenter was not always specified in the poll and various countries were reported, an intermediate EF of 25 $kgCO_2e$ TB^{-}1 was chosen.

Last, food EFs of 2.6, 1.1 and 0.5 $kgCO_2e$ per classic, flexitarian and vegetarian meal, respectively [34]. As they are not in the purchase listing, we considered water use, considering the annual volume in m^3 and 0.132 $kgCO_2e$ m^{-3} as EF for tap water distribution only [34], and waste, based on estimates of the volume and frequency of recollection for various waste type (mixed, plastic and paper—[17]). Raw data could not be gathered for LEFE and CESBIO. They were attributed per capita footprint based on the mean meal and waste footprints from the other four labs instead (S2 Table). Last, travel listings were used to estimate the footprint associated with hotel nights spent during travels. Thus, the number of nights was multiplied by country-dependent EFs in $kgCO_2e$ night^{-1} [35] (S1 Text).

2.3. Carbon footprint of research infrastructures

Beyond purchases, a new methodology is proposed to attribute a relevant share of emissions from the life-cycle of international, research infrastructures to individual laboratories, based on the scientific production (i.e., number of publications). Key elements of uncertainties associated to this approach for satellite or non-satellite infrastructures are discussed in 4.2 and 4.3.

2.3.1 General approach. Our new methodology is adapted from the one proposed by [27], targeted at astronomical space missions, including satellites, rovers and space probes.

Inspired by this pioneer study, we estimate the part of the total footprint of any infrastructure (subscript i), attributed to a given laboratory (l), and over a given time interval (Δt), with the following formula:

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

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

Thus, for each infrastructure, the three terms to be estimated are: (i) F(i), its footprint based on its construction and/or activity data (in $tCO_2e\ yr^{-1}$), (ii) Ss(i), is the share of usage related to research, as opposed to other usage (from 0 to 1), and (iii) the share of usage of the studied lab relative to all other labs (from 0 to 1) computed from the ratio at the center of Eq 1. This approach is particularly adapted for infrastructures which produce and deliver data to a broad community, for which the share of usage cannot be specifically attributed to any user, such as Earth observation satellite, in contrast to infrastructures for which each user has to declare a certain usage, for example beam time for a synchrotron, CPU time for a super computing center [32], or hours of observation in an astronomical observatory [27].

F(i) and Ss(i) are estimated for each infrastructure in the following subsections, and only the general algorithm was detailed to determine the share of the lab among the world scientific community (S3 Table). Given the various disciplines of the studied laboratories, and the fact that infrastructures do not necessarily maintain a publication list, we propose to use, by default, a generalist bibliographic database, the Clarivate Web of Science (WoS) database (S2 Text). Given the size of the database and the number of authors, we also simplify the approach of [27], by extracting first automatically M(i,Δt) and Ml(i,Δt) by querying the database to retrieve all work relating to the infrastructure i, over the period Δt, with or without a constraint on the authors' affiliations. Then, to avoid attributing several times emissions when an article using a satellite is signed by authors from several laboratories, we export the metadata of the Ml(i,Δt) articles and extract the mean proportion of individual authors from the studied laboratory among those (Af(i, l, Δt)). Authors with multiple affiliations were counted as fraction as if its part would be split between several institutions. We expect the number of publications associated with one infrastructure in a given laboratory to be highly variable on an annual basis. Thus, a 5-year average is assumed to allow a more representative estimate of the share of the infrastructure footprint that should be given to the lab. Thus, Δt = 2015–2019 was used for all infrastructures. For infrastructures which maintain a dedicated database of scientific publications, we applied our method on these databases in addition to the WoS database. We assume the dedicated databases to be more comprehensive and accurate, and use them for the final footprint attribution while we give the WoS results for comparison and discussion only. To constrain uncertainties and test an alternative, public bibliographic database we also discuss, for a few infrastructures, results derived from the Science Explorer database (S2 Text).

2.3.2 Satellite infrastructure. Using only scientific publications to determine the proportion of usage to attribute to each lab, implicitly assumes the whole footprint of any mission is only shared among the research community. This was expected for astronomical instruments but it is not obvious for Earth observation satellites. Thus, we excluded all satellite missions which are primarily designed for non-academic but operational purposes, typically weather forecast satellite (EUMETSAT, METEOSAT and GOES series for example) or GPS constellations, for which scientists are likely a negligible proportion compared to all other public and private users. We also limit ourselves to mostly international missions substantially used by the French research community.

As a result, 44 Earth Observation satellite missions were considered, several containing constellations or successive satellites (e.g., the Landsat series), amounting to 82 individual satellites (S3 Table). Most of these missions are mostly scientific, with access and usage restricted to experts, but not all of them. Some of them produce broadly used and broadly accessible data (e.g., the Landsat, SRTM or Sentinel missions; N = 11 out of 44, S3 Table) designed to be used by both private companies and public institutions, which are increasingly doing so for various applications. Hence, there was a need for these missions to determine their Ss(i), the share of the total footprint attributable to the scientific community. For the Sentinel missions, 30–60% of the 2019–2022 downloads on the ESA platforms were for research applications [36].

However, it is likely that a large share of downloads are done through other distributors such as Amazon AWS, or Google Earth Engine, where the proportions of non-scientific users may be larger. Thus, Ss(i) for these missions may range from 0 (e.g., a negligible share for scientists, as assumed for weather forecast or GPS satellites) to about 0.6 following the ESA report, so we used a central estimate Ss(i) = 0.4, as well as lower and higher values for discussion.

For satellite missions, [27] proposed to derive F(i) from either total mission cost, C, or launch mass, W. Yet, since mission cost is difficult to access, F(i) is derived from W, with a life-cycle emission factor of 50 (+/-10) $tCO_2e\ kg^{-1}$ [27,37], and dividing by the time in years between the first satellite launch (as several missions or programs had multiple launches) and the year of interest, here 2019 (S3 Table). The SRTM mission is an exception as it was fully operated through a Space Shuttle mission for which the weight factor cannot be applied and only the financial estimate was used, with and EF of 140 tCO_2e M€$^{-1}$. Emissions of recent missions, i.e. launched $>$ 2009, should nevertheless be distributed over a minimal timescale, Tmin = 10 yr, consistent with the approach of [27]. The impact of choosing Tmin = 20 yr on our results is also discussed.

2.3.3 Assessment and attribution of other non-satellite infrastructures. Non-satellite infrastructures involve, international infrastructure, some involving oceanographic missions, such as the IODP (Integrated Ocean Discovery Program) and the PIRATA (Prediction and Research moored Array in the Tropical Atlantic) programs, with frequent participation and use for the GET and LEGOS, respectively, while the In-Service Aircraft for Global Observation System (IAGOS) infrastructure, supported and used by the LAERO, relies on commercial aircrafts. The same approach as for the satellite was used, using Eq 1 and assuming Ss(i) = 1 for all infrastructures, and calculating the average annual footprint of each infrastructure. Typically, we estimate the fuel consumed by the ships or planes, in tons or m^3, and then convert it with an emission factor of 3.75 $kgCO_2eq\ kg^{-1}$ for diesel marine fuel or 3.83 $kgCO_2e\ kg^{-1}$ for kerosene [34]. For some infrastructure (depending on available information) we also assess air-travels, freight and purchases but always found it to be minor relative to the fuel use.

2.3.3.1 IAGOS footprint and share attributed to the LAERO. The (IAGOS) infrastructure relies on commercial aircrafts embarking instruments measuring atmospheric composition and meteorological variables along the flight [38]. The emission factor for scientific instrumentation on-board commercial flights is computed based on the "cost of weight" approach [39], widely used for estimating the fuel consumption due to additional weight embarked on airliners. It is retained because such scientific observations opportunely take advantage of existing airlines and airport infrastructures. Assuming a typical cost of weight of 0.035 kg of kerosene per kg of extra freight and per flight hour, we obtained an emission factor of 0.133 $kgCO_2e$ (kg freight)$^{-1}$ (flight h)$^{-1}$. This value only accounts for CO_2 radiative forcing but not for the additional effects of flight contrails. Thus, to be consistent with [15] and the other estimates of air-travel footprint, we doubled this emission factor, up to 0.266 $kgCO_2e$ (kg freight)$^{-1}$ (flight h)$^{-1}$. In 2019 IAGOS involved about 15 instruments weighing about 120 kg each with a total of 20,000 h of flight in 2019 (representative of the few previous years), yielding a footprint of 640 $tCO_2e\ yr^{-1}$. The footprint of the 15 instruments themselves is estimated to 105 $tCO_2e\ yr^{-1}$, with a financial EF of 0,7 tCO_2e k€$^{-1}$, a typical cost of 200 k€ and lifetime of 20 years, bringing the total footprint to 745 $tCO_2e\ yr^{-1}$. Note that the fleet of instruments is currently ramping up to reach 20–25, which may mean the total footprint (of both fuel and equipment) may also increase to reach 1–1.2 $ktCO_2e\ yr^{-1}$ in the coming years.

Querying WOS with the keyword 'IAGOS' and searching the dedicated publication database [40], we obtain a global share for the LAERO of 19% and 16% (S2 Text), respectively, representing 119 tCO_2e in 2019 when using the latter estimate.

2.3.3.2 IODP footprint and share attributed to the GET. For IODP, 85% of all missions are on board the Joides Resolution which use of 33, 17 and 7, tons of fuel per day for all its activities, during transit, station and harbor phases, respectively, as reported by the crew. Given the daily statistics of activity over 2013–2023 [41], we estimate an annual footprint of 24 ktCO_2e yr^{-1} for the Joides alone (S4 Table). The remaining 15% of missions are operated by a Japanese drilling ship and by third-party missions coordinated by a European consortium for which we could not gather detailed information but simply assume similar operating footprint which would rise the total by 15% to 27.5 ktCO_2e yr^{-1}. At first order, the footprint of flights taken by scientists to join the boat, may add about 1 ktCO_2e yr^{-1} (S3 Text), yielding a total footprint of 28.4 ktCO_2e yr^{-1}.

Querying WOS with the keyword 'IODP' and searching the dedicated publication database [42], we obtain a global share for the GET of 0.065% and 0.089% (S2 Text), respectively, representing 25.3 tCO_2e in 2019 when using the latter estimate.

2.3.3.3 PIRATA footprint and share attributed to the LEGOS. The PIRATA program involves Brazil, the US and France, and is about deploying and maintaining a network of moored buoys (currently 18) in the Tropical Atlantic. Limiting our analysis to 2015–2019, the cruise duration was estimated around 30 days per year per country, and number of embarked scientists dedicated to PIRATA (typically 6 to 16 depending on the mission), yielding a total of 5444 person.day at sea [43]. Based on technical data from the French Scientific ships and reported data for the Brown US ship, typical fuel consumption was estimated to 0.5 m^3 p^{-1} d^{-1} equivalent to 1.6 tCO_2e p^{-1} d^{-1} (S4 Text) leading to a 2015–2019 average of 1.7 ktCO_2e yr^{-1} (S4 Table). Then air-travels appear as negligible, but we estimate freight to add 0.1 ktCO_2eq yr^{-1} and the instrumented buoys themselves to add 0.4 tCO_2eq yr^{-1}, yielding a total annual footprint of the PIRATA infrastructure of 2.2 ktCO_2e yr^{-1} (S4 Text).

Querying WOS with the keyword 'PIRATA' and searching the dedicated publication database [44], we obtain a global share for the LEGOS of 4% and 5% (S2 Text), respectively, representing 110 tCO_2e in 2019 when using the latter estimate.

2.3.3.4 Other Oceanographic missions. In addition to these contributions to international research efforts some researchers may join ship cruises for their own research purpose which means their entire emissions should be attributed to their laboratory. For example, in 2019 at GET, one round trip mission to the Kerguelen islands was done by a researcher, which emits ~50 tCO_2e (S5 Text). In 2019 at LEGOS, there was the MOANA-MATY 2 mission, a cruise for the SURVOSTRAL program and two missions with unknown motives, with one scientist at sea for 24, 10, 9 and 6 days, respectively. Assuming the emission factor of PIRATA cruises holds (1.6 tCO_2e p^{-1} d^{-1}) yield a total footprint of 78 tCO_2e. Given no publication list nor consistent mention of the two former programs were found, we attribute the whole footprint to the LEGOS.

3. Results

With a comprehensive inventories of emissions, CF was estimated between 9.2 and 28.2 tCO2e p^{-1} for all labs except the LEFE at 5.5 tCO2e.p (Fig 1). Travels and purchases are systematically among the top 3 sources typically between 1.5 and 5 tCO2e p^{-1}. Then, the usage of satellite infrastructure is the primary source for three labs, between 8 and 12 tCO2e p^{-1}, while it ranges from third sources to negligible for the three other labs. Last, even though we account only for a few examples of other research infrastructures from the Earth Science community, the usage of single one may contribute ca 1 tCO2e p^{-1} to the laboratory. In contrast,commuting, meals and all building activities rarely exceeds 10–20% of the total CF (Fig 2). We detail below the results for each categories.

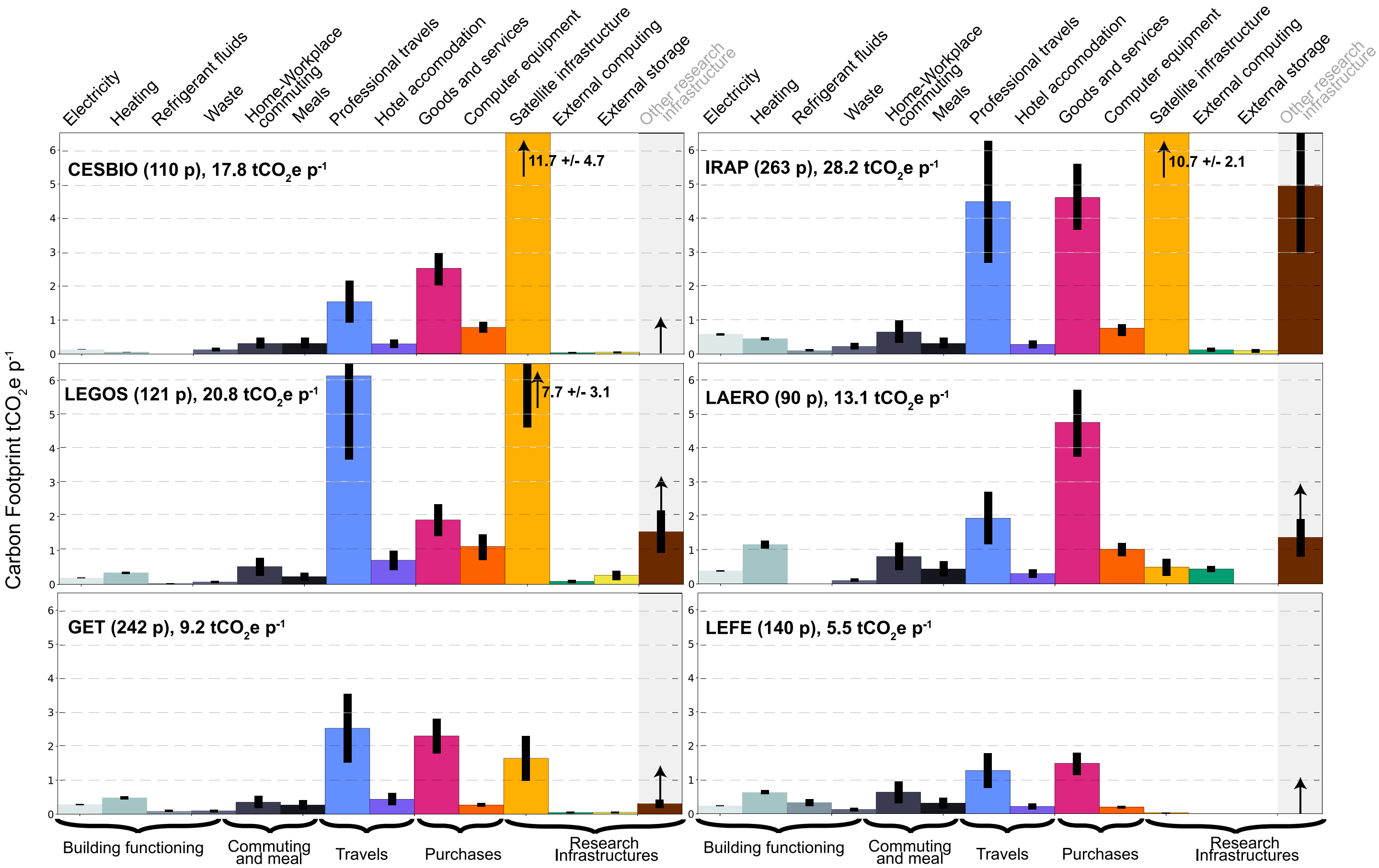

Fig 1. Carbon footprint in tCO_2e per person, for all laboratories activities, grouped by sectors. For all labs except IRAP, CF due to the usage of Other research infrastructures are incomplete, minimum estimates (as suggested by the arrow and grey zone) given that we could not gather enough information for all used infrastructures.

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3.1. Carbon footprint of research infrastructures

We start with synthesizing our results focusing on international research infrastructures that is the main novelty of our study. With our method, we estimated the annual CF of 44 satellite missions relevant to the Earth and environmental sciences, considered as individual infrastructure, to be ranging from 0.3 to 31 $ktCO_2e\ yr^{-1}$ with a median of 5 $ktCO_2e\ yr^{-1}$. The global share of attribution to laboratories are typically between 0.01 to 1% with a few outliers above 5% (Fig 3). These values broadly agree with estimates for astronomical satellite infrastructures [27], and to some extent to astronomical ground observatories, though the latter span a broader range of footprint (0.03 to 30 $ktCO_2e\ yr^{-1}$). We find no clear correlation between the age (first launch) of the satellite infrastructure and its footprint. This reflects the diversity of satellite weights through time and the fact that many old missions (amortized over long period) have had mission extensions (e.g., Landsat, ALOS, Jason) with successive launches increasing the total footprints. Overall, the 44 satellite missions considered in this study represent 6.3 $MtCO_2e$ (S3 Table), similar to the 4.9 $MtCO_2e$ estimated for the 46 astronomical space missions [27].

Turning to the aggregated footprint of all satellite infrastructures, it appears as the dominant share of the CO_2e budget for three laboratories, IRAP, CESBIO and LEGOS, equivalent

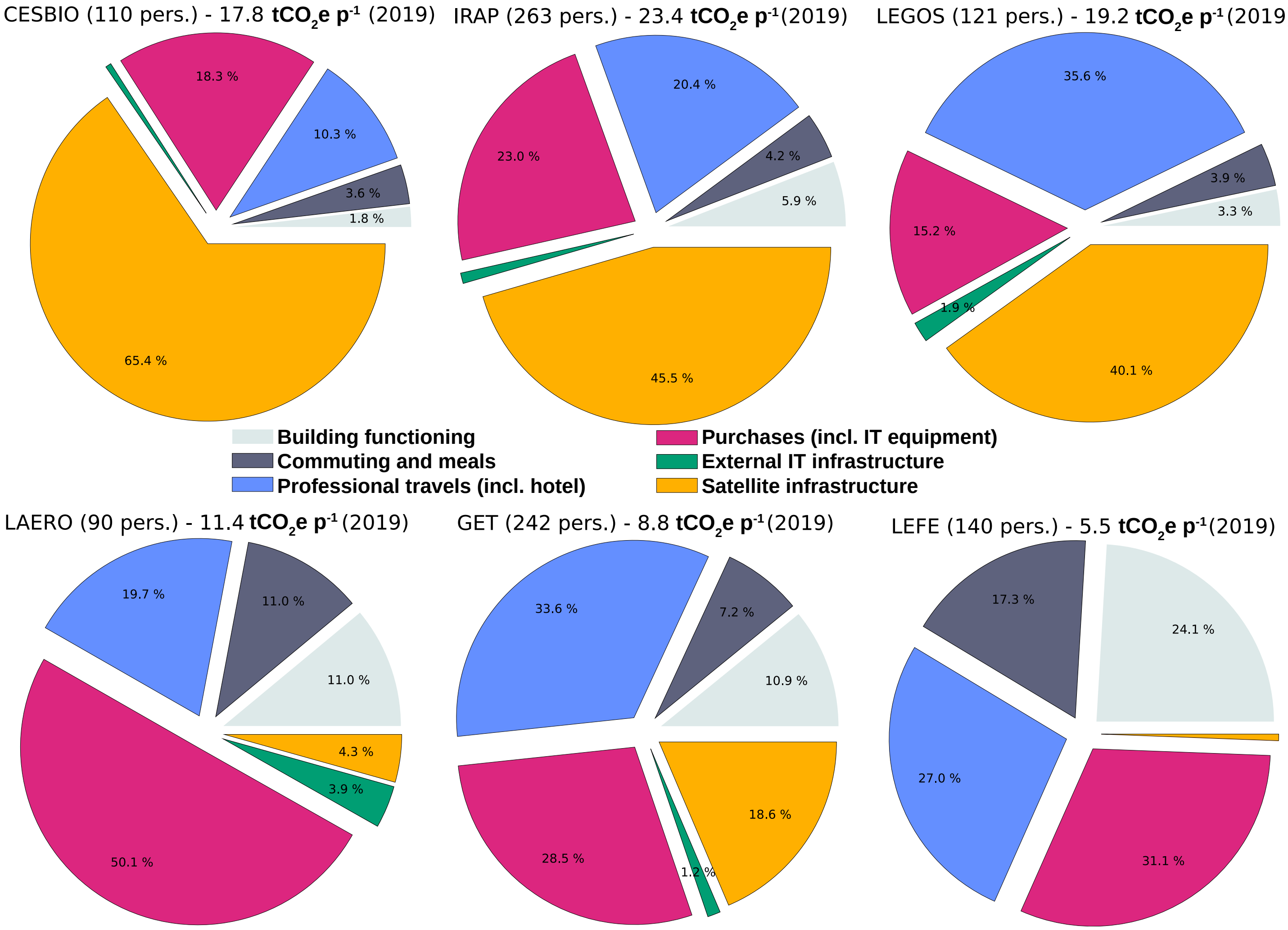

Fig 2. Proportions of the carbon footprint for the main sectors of activity of the six laboratories of the OMP, excluding the footprint of the use of other research infrastructure that could not be consistently estimated for each lab.

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to 2800, 1284 and 933 $tCO_2e\ yr^{-1}$, respectively, which is typically 40–65% of the total CF (Figs 1 and 2). LEGOS and CESBIO rely heavily on satellite infrastructures, as reflected by their numerous publications (263 and 417 over five years, i.e., 43% and 57% of the lab's publications, respectively) with keywords associated with a broad diversity of satellites, nearly 30 missions out of 44 (S3 Table). For GET and LAERO, where fewer researchers rely on satellite observations, we retrieve 150 and 43 publications (ca 10% of all) associated with 24 and 9 missions for the 2015–2019 period, which represents 1.6 and 0.5 $tCO_2e\ p^{-1}\ yr^{-1}$ or 398 and 45 $tCO_2e\ yr^{-1}$ for the whole laboratory, respectively. For the LEFE, with only 5 publications (1%) associated with 5 satellites over 5 years, the footprint is below 5 $tCO_2e\ yr^{-1}$ at about 0.03 $tCO_2e\ p^{-1}\ yr^{-1}$.

Turning to other infrastructures, for GET, IODP and ship missions to the sub-Antarctic region result in moderate footprints of 25 and 50 tCO_2e, respectively, adding 0.3 $tCO_2e\ p^{-1}\ yr^{-1}$ to the laboratory. For LEGOS, the PIRATA infrastructures and other oceanographic missions have an estimated footprint of 110 and 78 tCO_2e, respectively, representing 1.6 $tCO_2e\ p^{-1}\ yr^{-1}$ together. For the LAERO, the IAGOS infrastructure is estimated to be 119 $tCO_2eq\ yr^{-1}$ or 1.1 $tCO_2e\ p^{-1}\ yr^{-1}$.

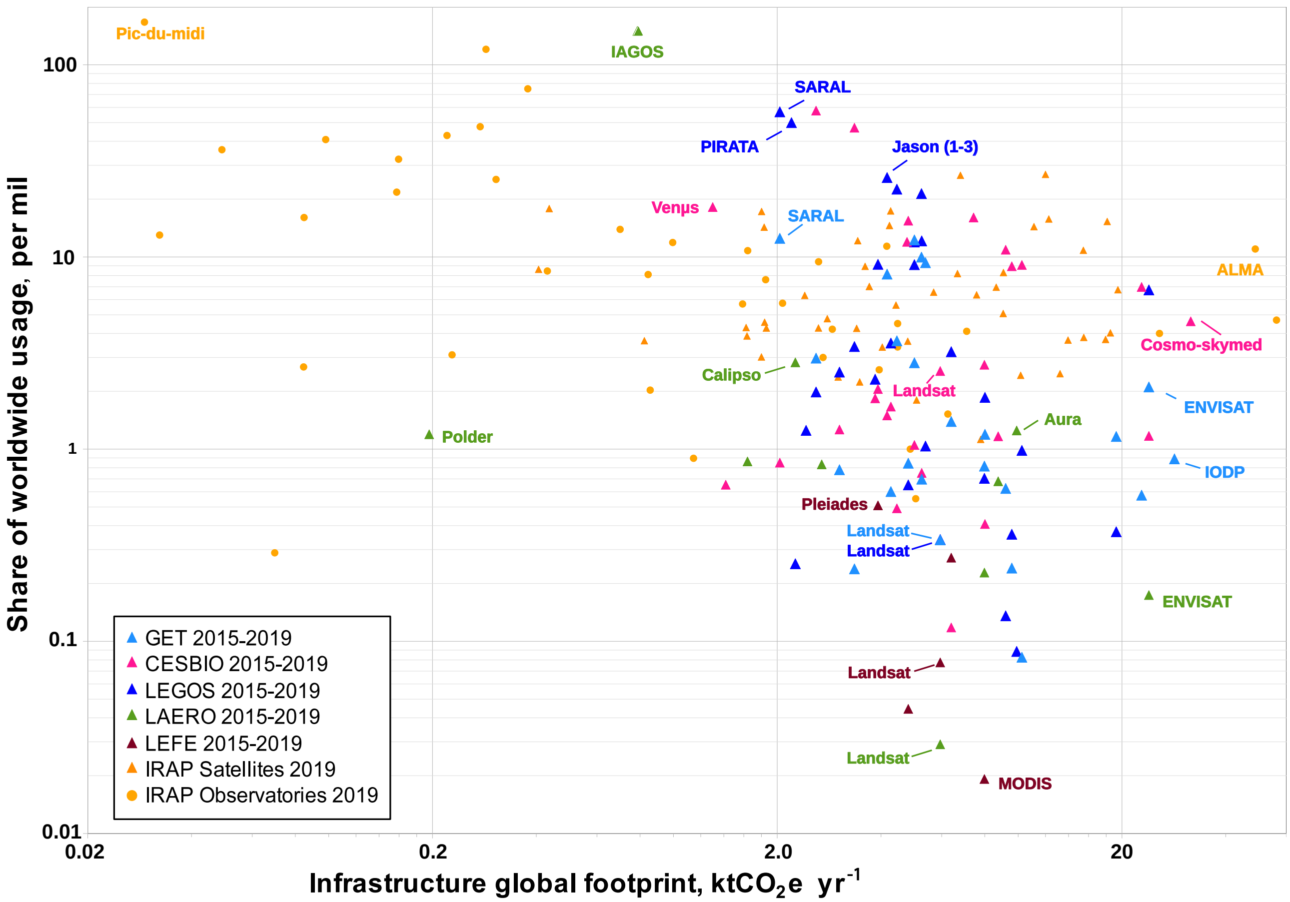

Fig 3. Share of usage of infrastructures by each laboratory against the annual footprint of the studied research infrastructures. Uncertainty estimates on both individual footprint and usage share is at least 20–40% (see 4.2). Several examples of infrastructures are named for references. For IRAP we differentiate ground observatories and satellites, as derived with a similar methodology [27], while for the other laboratories, all infrastructures are satellites (S3 Table) except IODP, PIRATA (ships) and IAGOS (aircrafts).

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These infrastructures display footprint and attribution in the broad range of the satellite infrastructures and of astronomic infrastructures (Fig 3) and are consistent with the typical footprint attributed to one laboratory for individual satellite mission, mostly between 10 and 100 $tCO_2e\ yr^{-1}$ (S3 Table).

3.2. Carbon footprint of laboratory purchases

Purchases are also a major share of the CF, between 2 and 5 $tCO_2e\ p^{-1}\ yr^{-1}$ for the studied laboratories (Fig 1), which typically represent 15–40% of the whole footprint (Fig 2), highlighting the need to consider a comprehensive inventory of scope 3 emissions when estimating GHG budget for research laboratories [24]. In all labs, IT equipment is representing a substantial share (>10–20%), between 0.21 and 1.08 $tCO_2e\ p^{-1}\ yr^{-1}$ for LEFE and LEGOS, respectively (Figs 1 and 4). Though modest general supplies (buffet, furniture, etc) represent between 0.13 and 0.25 $tCO_2e\ p^{-1}$ for LEGOS and LEFE, respectively. Then, the major sources depends on each laboratory research focus (Fig 4). Biology/Chemistry are major for GET (0.75 $tCO_2e\ p^{-1}$) and LEFE (0.82 $tCO_2e\ p^{-1}$) and to some extent LEGOS and LAERO (ca 0.35 $tCO_2e\ p^{-1}$), Field Equipment/Campaign are major for LEGOS (0.68 $tCO_2e\ p^{-1}$) and LAERO (1.96 $tCO_2e\ p^{-1}$)

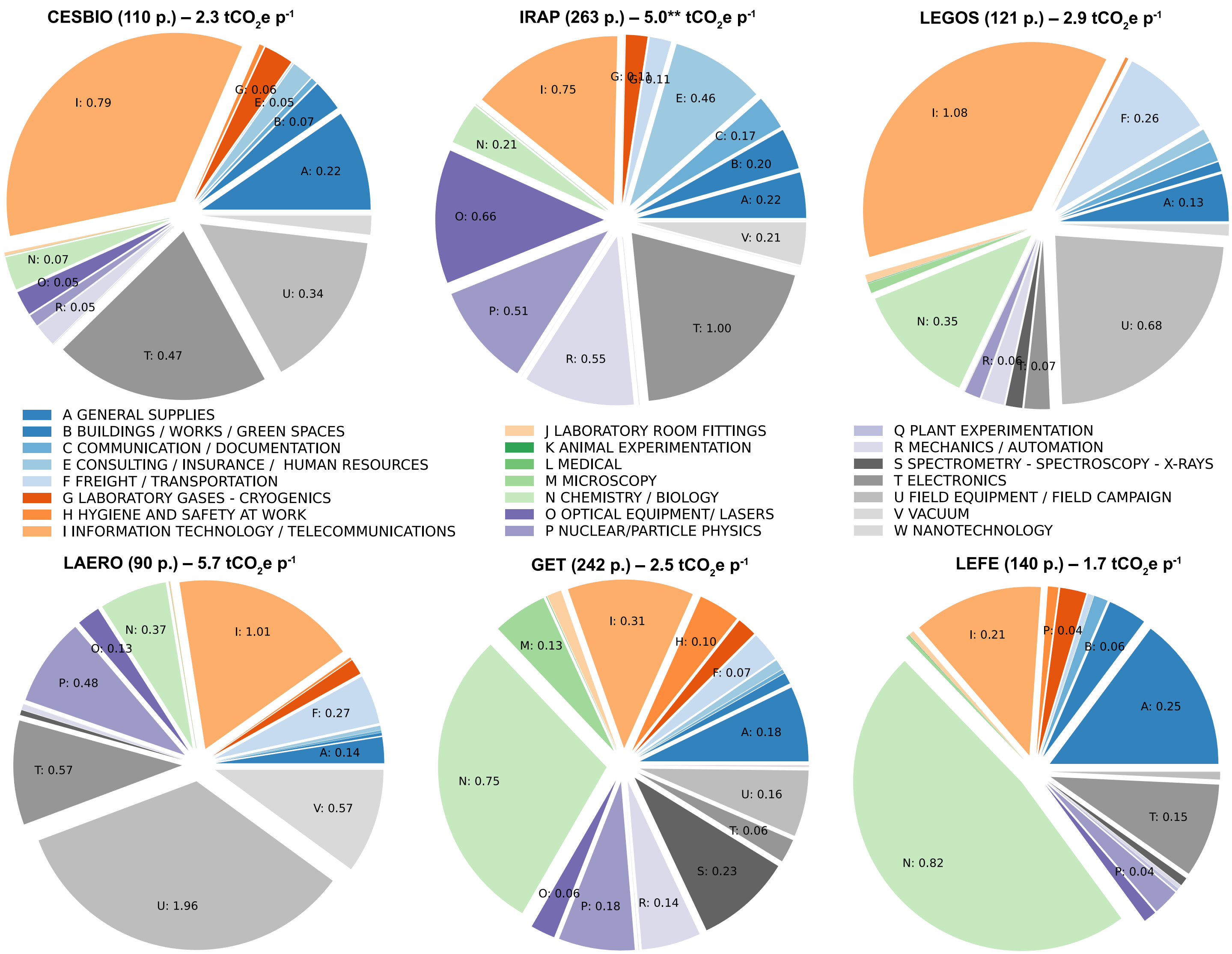

Fig 4. Distribution of the carbon footprint of purchases, grouped by categories for each of the six studied laboratories. Number on the pie chart indicates the amount in $tCO_2e\ p^{-1}$ for the given category. Note that the diagram for IRAP excludes categories with share <2% of the total, and thus only represents the main categories amounting to 5 $tCO_2e\ p^{-1}$ out of a total of 5.4 $tCO_2e\ p^{-1}$ [31](S2 Table)).

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and to some extent CESBIO (0.34 $tCO_2e\ p^{-1}$), while Electronics are major for CESBIO (0,47 $tCO_2e\ p^{-1}$) and IRAP (1.0 $tCO_2e\ p^{-1}$). Nevertheless, in each lab a non-negligible share of the CF remain distributed over a diverse range of purchases as the four categories with largest CF represent together between 55% (GET, IRAP) and 80% (LEFE, LEGO, LAERO, CESBIO) of the total purchase CF (Fig 4).

As expected, the total emissions from purchases are strongly correlated to the total financial budget of the laboratory ($R^2 = 0.95$) with a mean footprint of 424 +/- 47 $tCO_2e\ M€^{-1}$ spent (excluding travel expenses), which indicate an average carbon intensity relatively constant even though the purchases are distributed over different categories according to each lab (Fig 4).

Beyond IT equipment of the laboratories, the use of external IT infrastructure also represent a minor increase of the footprint, about 0.1 to 0.5 $tCO_2\ p^{-1}\ yr^{-1}$. This value, however, is uncertain and probably underestimated, because of its reliance of a poll with a limited response level, except in LAERO where most researchers relying on external IT where individually asked about their practice.

3.3. Carbon footprint of professional travels

Professional travels also represent a major share (in the top 3 for all laboratories) of the CF, with a mean of 3 tCO_2e p^{-1} yr^{-1} (Fig 1). In all cases, air-travel represents more than 80–90% of the total travel emissions, consistent with the fact that it also represents more than 70–80% of the distance traveled. As a result the total traveled distance is strongly correlated with the total travel footprint (Table 1). The spread in travel emissions and traveled distances seems related to the structure and focus of the laboratories. At the upper end with 6.1 tCO_2e p^{-1} yr^{-1} the LEGOS has many researchers funded by a national research institute focused on collaboration with the Global South countries, likely explaining its intense traveling practice. At the lower end with 1.3 tCO_2e p^{-1} yr^{-1}, the LEFE has most of its researchers with teaching duties and most of its research field areas in Southwest France and the Pyrenees.

Also, even if it may be somewhat overestimated, the CFs for hotel nights are substantial from 0.21 to 0.71 tCO_2e p^{-1} yr^{-1}, and are greater than commuting emissions for 2 laboratories, GET and LEGOS.

3.4. Carbon footprint of laboratory in situ operations

Last, we find that the general in-situ operations, made of the building functioning and the meal and commuting habits of the laboratory staff represent a minor share of the footprint for all labs except LEFE. Electricity consumption represents between 0.1 and 0.5 tCO_2e p^{-1} yr^{-1}, while the heating footprint is between 0.3 and 1 tCO_2e p^{-1} yr^{-1}, except for the CESBIO which benefits from a heating system based on biomass and thus has a much lower footprint of 0.05 tCO_2e p^{-1} yr^{-1}.

Note however that the electricity mix in France has a low carbon intensity. With an average world carbon intensity, the footprint would have been about eight times larger than it is [24] and become a major share.

Refrigerant fluids used by some labs in cooling systems add 0.01 to 0.3 tCO_2e p^{-1} yr^{-1}. The footprint of water use is estimated to be less than 0.01 tCO_2e p^{-1} for all laboratories, thus excluded from figures for simplicity, while waste disposal is estimated to represent between 0.07 and 0.23 tCO_2e p^{-1} yr^{-1}.

Turning to staff practices for daily commuting to reach the laboratories, it represents between 0.3 and 0.8 tCO_2e p^{-1} yr^{-1}. The studied laboratories often have nearly 50% of the total commuting distance traveled by bicycle, train or public transports with very low emissions, while the rest is mostly traveled by car which dominates the emissions. Meals taken at the workplace represent between 0.23 and 0.45 tCO_2e p^{-1} yr^{-1}, the spread reflecting the diversity of diet habits. Summing all these items yields a footprint of 1.0 (for CESBIO) to 2.9 (for LAERO) tCO_2e p^{-1} yr^{-1}, representing less than 10% of the total CF for the laboratory intensively using infrastructures, about 20% for GET and LAERO and up to 40% for the LEFE (Figs 1 and 2).

4. Discussion

Our key result is that a comprehensive inventory of emissions yields large carbon footprints (CF) above 10 tCO_2e p^{-1} yr^{-1}, for most Earth, environmental and space science labs, with a strong dependence on research focus and methodologies. Indeed, the three lab focusing on remote sensing have the largest total CF (18–28 tCO_2e p^{-1}) with the largest share of the CF related to the use of satellite infrastructures (Figs 1 and 2). In contrast, LAERO and LEFE which have thematic relatively close to the ones of LEGOS and CESBIO, have CF two and three times smaller respectively, due to their limited usage of research infrastructures, leaving purchases and travels as largest share. In this context of differentiated CF structure, we thus discuss in this section (i) these footprints compared to other recent works, (ii) the uncertainties, (iii) the limits of some classical reduction measures, and (iv) structural changes in scientific institution that may favor low-carbon knowledge production.

4.1. Comparison of our carbon footprint estimates with recent work

The carbon footprints of the studied laboratories are significantly above many previous estimates for European institutions. However, excluding research infrastructures, they still fall within the range of other European universities or research institutes (about 10 $tCO_2e\ p^{-1}\ yr^{-1}$, [26]) and other French laboratories both in terms of travels (1–3 $tCO_2e\ p^{-1}\ yr^{-1}$) and expenses (2–4 $tCO_2e\ p^{-1}\ yr^{-1}$; see [15,24]). We note that our estimate of carbon intensity for purchases, 424 +/- 47 tCO_2e M€$^{-1}$, is about 30% higher than the estimate of [24] for 107 French science and technology labs, at 320 +/- 100 tCO_2e M€$^{-1}$, (though their uncertainty range overlaps). This may be in part a bias due to a different set of financial emission factors but also reflects slightly different distributions of purchases in our sample of studied labs. In any case, our main conclusions would not be affected, and a more robust methodology for a future work is recommended. Besides, this financial approach that links prices and GHG emissions, depends on the time when these factors were computed, and year-to-year comparison should acknowledge general price inflation, which has no link with physical GHG emissions.

4.2. Uncertainties on the carbon footprint related to using satellite infrastructure

For the estimated footprint of Earth Observation satellite, we list several potential sources of uncertainties that should be addressed in future works. First, as identified by [27], the uncertainties on the emission factor (50 $tCO_2e\ kg^{-1}$or 140 $kgCO_2e$ M€$^{-1}$) remain large (at least 20–50%) and estimated based on a few cases only, and we urge actors from the space sector to release and publish additional estimates for various satellite missions. At this stage, we have no way to differentiate the footprint of a new versus a follow-up mission, or a mission made of one large satellite versus many small satellites (e.g., cubesats or nanosats) of same total weight. Then, the bibliographic attribution of each satellite (or other infrastructure) to a given lab, has its own uncertainty based on the content of the database (e.g. Science Explorer (SciX) is incomplete outside of Earth and space Sciences), and then on the accuracy of the retrieving query (e.g., Web of Science (WoS) does not allow full-text search). Based on three infrastructures with dedicated publication list, the uncertainty in global share estimates for individual infrastructure may be between 20 and 40%, both for WoS and SciX database (S2 Text). These uncertainty estimates should be refined, but assuming they are uncorrelated, the final uncertainty on the total CF attributed to a lab and including 10–30 infrastructures would be 3–5 times smaller thus about 20–30%.

Another issue is the time over which the total life-cycle footprint of a satellite is distributed over a timescale to derive an annual footprint. Following [27], we impose a minimal timescale, assumed to be Tmin = 10 years. Assuming Tmin = 20 yr would reduce the footprint by about 15% for most laboratories, 20% for the GET and 25% for the CESBIO, but would leave satellites as a top source of CO_2 in the laboratories intensively using them. We consider unlikely to have Tmin>10–20 years because many missions regularly launch instruments to insure the continuity of the dataset, e.g. every 10–20 years as for Landsat, SPOT, GRACE, JASON. . . (S3 Table).

Another major uncertainty is on Ss(i), the share to science. Indeed, many satellites used by Earth scientists have multiple applications (military, meteorological, industrial . . .) and we could find no specific way to estimate the share of usage of each applications. We assumed a typical value of Ss(i) = 0.4 based on users' reports of the Copernicus Sentinel satellites and applied this for 11 missions (S3 Table). If those missions had Ss(i) = 0.2 or Ss(i) = 0.6 the satellite footprint would only change by +/-5% for GET, LEGOS, and LAERO reflecting the fact that many of the satellite they use, are more specialized (e.g., for gravimetry, ocean waves or atmospheric chemistry). In contrast, the change would reach 15% and 20% for the CESBIO and LEFE, respectively. Consistently, setting Ss(i) = 0 for these 11 missions would reduce even more the total satellite footprints by about 10% for GET and LEGOS, 15% for LAERO, 30% for CESBIO and 40% for LEFE. Last, if we maintain Ss(i) = 0.4 for the same 11 missions and assume a public/commercial use for all other specialized missions, i.e., setting Ss(i) = 0.6 for those, the satellite footprint would be reduced by 30–35% for most laboratories (S3 Table).

Thus, while uncertainty from the EF and the attribution methods of [27] yielded and uncertainty on the total CF of about 20% [31], we consider that accounting for the additional uncertainty on Tmin and Ss, the uncertainties for Earth and environmental science satellite infrastructures is more likely about 40%, and should be further investigated in future work. Nevertheless, even with these larger uncertainties, we conclude that satellite infrastructures may remain the primary contribution to the total CF of laboratories using intensively remote sensing for their research.

4.3. Uncertainties on the carbon footprint related to other infrastructures

Attempting to constrain the footprint of other type of research infrastructures is even more challenging, given their diversity in size and nature. Important pioneering examples come from astronomy and astrophysics [27,28,45], meteorology [46], or particle physics [29]. Still, the example of IRAP shows that the CF related to the use of 47 ground infrastructures may reach nearly 20% of the total (5 $tCO_2e\ p^{-1}$) (Fig 1), with an uncertainty of 40% [27,31]. For the other studied laboratories, we only managed to constrain the CF of a few infrastructures adding 0.3 to 1.6 tCO2e p^{-1} for three laboratories. The uncertainties on these may be well below 40% as in contrast to [27], we do not use a financial EF but mostly a physical approach based on fuel use.

However, the main issue is rather that we miss multiple infrastructures, that includes (at least) the ship-based observatories in which LEGOS is involved such as SONEL and SSS (S6 Text), various ground observatory or long-term monitoring infrastructures, such as HYBAM, AMMA-CATCH, and M-TROPICS for the GET or OSR-SO for CESBIO (see [47,48] for more detailed listings). We do not include these infrastructures because we could not complete a minimal inventory allowing to estimate accurately their footprint whether it comes from fuel, purchases, and/or travels. Thus, in contrast to satellite infrastructures, for which our list represents a substantial fraction of the global research satellite infrastructures (S3 Table), our sample for other infrastructures is only composed with ~10% of the global community infrastructures.

Thus, we encourage efforts in assessing the CF of more Earth and environment science research infrastructures. First, because infrastructures may increase substantially the global footprint of laboratories, as it was the case for IRAP. Second, because considering infrastructures may allow to correctly attribute emissions, and associated responsibilities, by removing some sources from a given lab and redistributing it globally to all users. For example air-travels to reach an IODP oceanographic cruise, as well as days at sea, should not be entirely attributed to the footprint of the laboratory performing the mission but to all scientists that will benefit from the data. For example, for the GET, the direct and entire attribution of all days at sea with

IODP in 2019, assuming a typical footprint of 1.6 $tCO_2e\ d^{-1}\ p^{-1}$ (S4 Text, S4 Table) would represent 672 tCO_2e, more than 20 times the 25 tCO_2e we obtain with our method (Eq 1, Fig 3). This may also be the case for instruments acquired by a given laboratory but actually deployed within an international, ground observatory. For example, the average annual operations of OSR-SO by CESBIO, including electricity, road travels and purchases, represent about 63 $tCO_2e\ yr^{-1}$ among which 44 tCO_2e of equipment purchases, which represent 17% of the CESBIO non-IT purchases and are currently attributed entirely to the CESBIO. Given that the CESBIO contributes >90% of the equipment of this ground observatory, a formal assessment of the footprint of this observatory and of its usage by CESBIO would probably reduce somewhat (by up to 3%), the global footprint of the CESBIO. Similarly, for LAERO we could not track some purchases and travels performed to support the IAGOS infrastructure, which therefore should not be entirely attributed to the LAERO (but only 16% of it). In contrast, attributing to the studied labs a share of footprint associated to observatories managed by other laboratories would increase their footprint. For now, it is unclear whether attributing properly the footprint of these medium scale infrastructures will increase or decrease significantly the budget of the studied laboratories. In any case we argue in favor of estimating the CF of large infrastructures and attributing it to the laboratory using them, rather than to the entire communities [e.g., 27]. First because defining and assessing the number of scientists involved in large, interdisciplinary community, such as Earth and environmental sciences, may be challenging, and second because this approach may dilute the responsibility over many more scientists not directly involved into the infrastructure usage (and thus planning and deployment) and reduce the attention and effort that the community may take to reduce the footprint of its infrastructure (see 4.4).

4.4. Typical reduction measures and their quantitative impact

The comprehensive CF allow us to estimate the effects of typical measures aiming at reducing GHG emissions. Given the diversity of size and practice of the studied laboratories, we present the relative effect of these measures, although their effect in terms of saved tCO_2e may be quite variable. Importantly, we give the average effects of such measures for laboratories with substantial infrastructure footprint and for the two laboratories where the usage of infrastructures are a small part of the budget (LEFE and LAERO).

We first start with the commonly discussed measures related to building efficiency or daily practice such as diets and commuting habits. Measures allowing to reduce by 50% electricity and heating, as prescribed by the French national low-carbon strategy, would typically yield global reduction of 1 to 3% and up to 4 and 7% for the LAERO and LEFE. Carpooling and modal report to bike and public transport would represent a drop by only 0.5–2% of the global footprint if they achieve a global reduction by 50% of the commuting distances by car, but up to 3 and 6% for the LAERO and LEFE. A similar reduction of 0.5–2%, would be obtained if halving the footprint of lunch meals (e.g. with more vegetarian diet and no red meat; [49]). Measures targeting waste or water would have even less impact on the total CF. Thus, achieving all these measures would require substantial efforts but have a limited impact. Even for the LEFE, the reduction would remain about 15% only.

Turning to measures that would affect professional practices but with limited impact on scientific output, we could envision measures affecting mobility and equipment. For example, imposing train travel within the metropolitan French territory would reduce the total laboratory footprints by 2–3%. More substantial reductions could be achieved by targeting long distance flights and frequent travelers. Indeed, the distribution of flights is often very uneven, with few individuals representing a large share of the total air-travel footprint [17,18,50]. Thus, flight quotas, which are already experimented by pioneer laboratories in France [e.g., 51], could have a reduction impact of up to 20–60% of the travel footprint [18]. Various implementation of quotas are possible (e.g. by research team, reportable over 2 or 3 years, accounting for career stage, etc.). For a first-order estimate, we consider a flight quota of 10,000 km p^{-1} yr^{-1}, attributed to each researcher (i.e., including PhDs but not support staff, thus typically 60–70% of the total staff, Table 1). Assuming all staff fully-use its quota and an average emission factor between medium-haul and long-haul flights (i.e., 0.17 kgCO2e km^{-1} as in [18]), we obtain a reduction varying between 0% (LEFE) to 80% (LEGOS) of the 2019 travel footprint, which means 0–23% of reduction of the comprehensive footprint (Fig 5). Note that these numbers would increase by a few percents if we considered a stricter limit of 5,000 km per year or if we considered only 50% of the quotas would be used. This is one of the most impacting measures for IRAP and LEGOS, that have but it may be resisted due to the potential correlation between travels and visibility and career [50,52]. 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 French laboratories (~7%, [18]).

In terms of purchases, a detailed impact analysis of seven measures to reduce expenses was performed by [24] over a large database of French laboratories. Most measures focused on 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% [24], which would mean a reduction of 7 to 13%, and up to 20 and 17% for the LAERO and LEFE (Fig 5). The single measure of halving IT Purchases by extending their lifetime represents a reduction of 2% for several labs and 6% for the LAERO. Whatever the

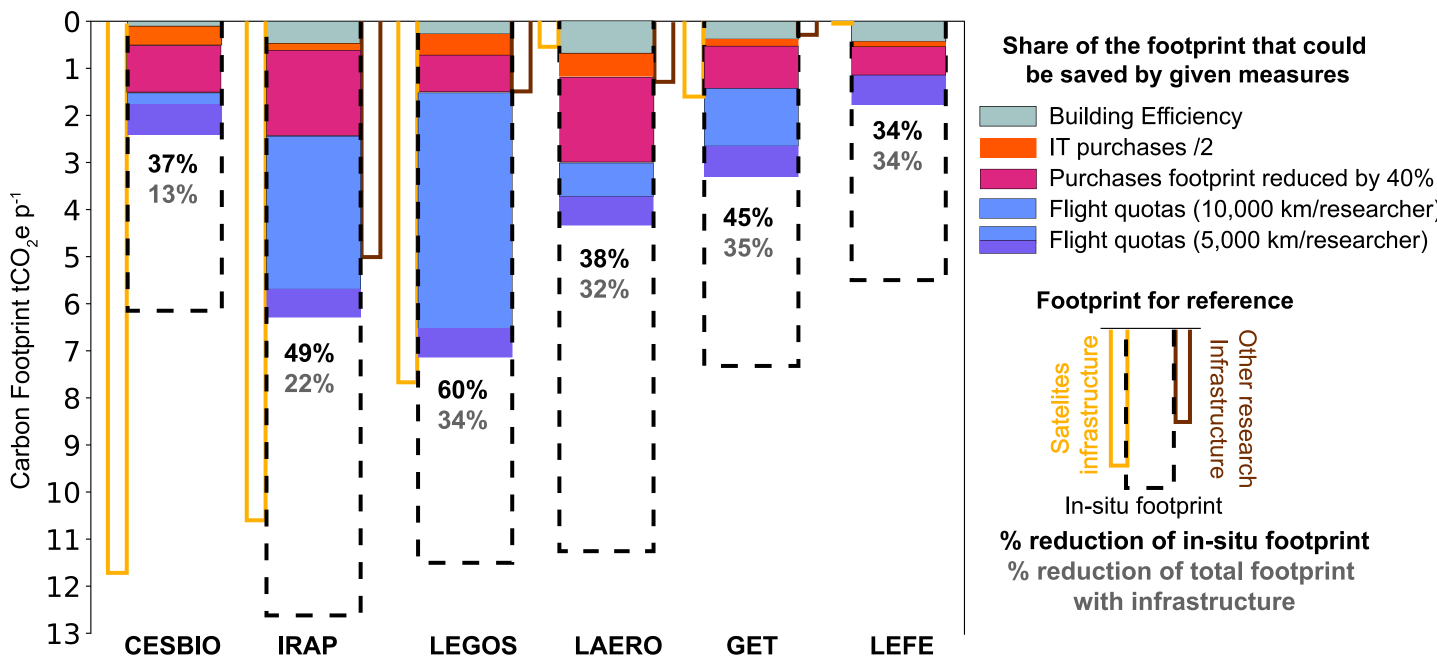

Fig 5. Potential reduction of the footprint achievable through a set of measures (halving building electricity and heating; halving IT purchases; 40% reduction of the purchases footprint following the measures of [24]; and flight quotas), compared to the current total in-situ footprint (dashed) and the research infrastructure footprints for each laboratory. The numbers indicate the total achievable reductions in % of the in-situ (black) and total (= in situ + infrastructures, grey) footprints.

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associated impacts, if all measures would be applied together, they would achieve 15–20% reduction for labs relying most on research infrastructure (CESBIO and IRAP) but about 35% for other labs (Fig 5).

The large share of research infrastructures, 8–12 and 1–5 $tCO_2e\ p^{-1}\ yr^{-1}$ for the three labs using the most satellite infrastructures and other infrastructures (Fig 1), respectively, is strictly capping the potential of reduction (in relative value). Reducing substantially the CF due to using research infrastructures cannot be limited to decarbonizing the existing ones, by greening their fuel or production process when possible. It also likely requires a reduction of the frequency and/or size of the newly deployed infrastructures [27]. Given that research infrastructures are by definition objects shared and managed by large communities, often international consortia, the challenge of defining a sustainable strategy for research infrastructures is by essence collective and political, and thus is beyond the hands of any single scientist or laboratory. Nevertheless, EESS scientists are often consulted at early stages of the development and deployment of research infrastructures. Thus, they could make funding institutions and space agencies aware of the CF of research infrastructures and encourage them to adopt and implement carbon budget limits in their development plans. This would favor more work in the sustainability assessment, allowing to assess the CF of competing infrastructure projects [e.g., 30], and ultimately favor infrastructures with low CF, as well as research questions and methods balancing infrastructure needs and sustainability.

4.5. Institutional changes toward low-footprint research activities

We discuss in this section structural changes in the organization of public research that may allow more substantial reduction of laboratories footprint (carbon but not only) and facilitate the implementation of measures presented above, including a long-term reduction of the size and/or number of research infrastructure.

First, we recall that, the global number of publications (a typical indicator of scientific output) has been growing exponentially for decades [53], probably mostly because the number of publishing scientists, across disciplines, also increased significantly [54,55]. While its maintained, such growth would mechanically increase the total footprint of research activities, in an unsustainable manner. This questions the increase of scientific activity, even if the total carbon budget allowed to scientific disciplines may be evaluated as a function of the benefits its brings to society, though assessing the societal impact of science remains a difficult and debated task (see review by [56]).

Beyond strategies to limit the growth in the number of scientists, substantial reduction in per capita footprint is likely to require a rethinking of science allowing scientists to produce societal benefits with reduced (i) travels, (ii) purchases and (iii) usage of research infrastructures, which are the pillar of the CF reported here for EESS. In this sense, it is interesting to note that while all labs have similar publication rate, the LEFE which has a CF two to five times lower than the other labs, has the lowest budget per capita, the lowest travel distance by capita and the lowest usage of infrastructure (Fig 1, Table 1). Thus, although research topics are not strictly comparable between LEFE and the other labs, it does suggest that scientific production may be maintained while reducing the activity driving the CF.

We suggest that this goal of simultaneously reducing lab activities and footprint while preserving scientific production, could probably be achieved by rethinking (some) scientific institutions toward the framework of "slow-science", i.e., "doing less but better" [57–60] which would also likely improve working conditions and health [61] and reduce incentives to scientific misconduct [62,63].

Such "slow-science" framework would imply promoting and organizing collaboration rather than competition, for example by rethinking some evaluation indicators, especially individual indicators [64]. This would facilitate the pooling of equipment and infrastructures (at various scales) rather than their duplication, and reduce the need for long-distance travel to acquire new data by using instead a fair network of collaboration with international colleagues, both allowing to reduce major sources of GHG emissions. Additionally, (re)turning to recurrent collective funding instead of episodic individual funding grants (which themselves consume substantial researcher time), could allow to avoid the incentive to "use up" remaining funding (at the end of the year or of the project) into equipment. More indirectly, it could favor work focusing on analyzing and interpreting archived data rather than work pushing for novel data acquisition (i.e., new machines, field-campaigns or infrastructures) through large grants, since databases from measurement campaigns are rarely fully exploited.

Last, promoting broader recognition of the role of scientists within society (actionable and socially-relevant science, see [56]) rather than only focusing on innovation and mere knowledge production, could also allow scientists to spend more time on academic activities that can be achieved locally, with low-tech equipment and/or no or reduced research infrastructures. Such activities could include research-actions or participatory-science [65], developing collaboration with policy centers, or ethics-driven engagement in various ways with diverse types of public to promote systemic understanding of the ongoing crisis and its link with social, political and economic institutions [66,67]. This last proposition is important as greater scientific engagement is expected by the public (e.g., on issues related to climate change [68]), does not appear to compromise scientific credibility [69], while it could contribute to more rapid mobilization and adoption of political measures to address the climate and biodiversity emergencies [67,70]. Another general direction includes reflexive approaches of (geo)sciences in which we analyze our own scientific activity, frequently with an interdisciplinary approach including social sciences, trying to address interconnected questions such as how, why, for whom, and with what consequences we work (see recent examples in geosciences, [71,72]. These activities would require no or little purchase or research infrastructures and could be promoted by being explicitly valued within guidelines of academic committees (for recruitment or promotion).

5. Conclusion

We presented a comprehensive estimate of the green-house gas footprint of six laboratories from the Earth, environmental and space sciences (EESS). The main novelty of these budgets is that the scope 3 also includes purchases and the use of research infrastructures, and notably satellite infrastructures. We have generalized the methodology of [27], to attribute a meaningful fraction of the total footprint of a research infrastructure to a given research laboratory. This fraction is obtained by counting the affiliated authors among publications associated with the infrastructures, retrieved from the global Web of Science database (and could be applied alternatively on the Nasa Science Explorer database). The method is applied to 44 satellite missions used by geoscientists as well to 3 other international infrastructures relying on ships or planes. Consistently with [27], we found that the use of satellite infrastructures is the largest share of the footprint for the three laboratories intensively using remote-sensing, between 40 and 65%, reaching 8 to 12 tCO2e p^{-1}. Other type of research infrastructures were only partially assessed, but their use represented up to 1.5 tCO2e p^{-1} in Earth science labs, and a comprehensive integration of all research infrastructures into the GHG footprint of laboratories remains a challenge for future work. Together with infrastructures, air travels and purchases represent other major shares of the budget, typically each between 1.5–5 tCO2e p^{-1}, and bring the annual footprint above 9 tCO2e p^{-1} for five out of six laboratories. In contrast, the laboratory with the smallest footprint (5.5 tCO2e p^{-1}) barely uses international research infrastructures, and had in 2019 the smallest purchase budget and travel distance (by capita). As a consequence, radical footprint reduction strategies, based on flight quotas and diverse reductions of purchased equipment may reach reductions between 35% and 60% of the in-situ laboratory footprint (i.e. without satellite and other type of infrastructures), but is limited to reduction of 15–35% of the total footprint for laboratories intensively using research infrastructures. We finally suggest that a deep reorganization of scientific activities away from a competitive, grant-based, innovation-focused paradigm may be an essential step for more sustainable scientific practice.

To remain exemplary and thus contribute to political actions towards addressing ecological emergencies [7,8,67], we urge the EESS community, to publicly engage into quantitative plans for ecological footprint reduction. For example, laboratories, departments, or institutes could commit into targets consistent with the 6th IPCC report [1] with a reduction target of about 45% of their 2019 in-situ footprint achieved by 2030, and continued reduction beyond this date, as already pioneered by some laboratories [51]. In parallel, we call on collective discussions across the EESS community, including large organizations such as the American Geophysical Union and the European Geosciences Union, funding agencies, and space agencies, toward rethinking the deployment of new infrastructures. Indeed, a reduction in size and deployment frequency of new research infrastructures is probably the only way to reduce the overall environmental footprint of EESS scientific institutions [73]. We believe that these two specific goals, rather than being seen as punishments or limitations, should be embraced as a stimulating, long-term challenge for the emergence of a more sustainable, meaningful and healthier scientific practice, at the individual and collective scale [58,60,61].

Supporting information

S1 Table. Listing of NACRE codes and their associated emission factors derived from the ADEME's Base Carbone, and used to convert purchases from financial listing into equivalent CO2e emissions. Only the codes relevant to at least one of the six laboratories were given a non-null value.
(XLSX)

S2 Table. Estimates of carbon footprint for each sources in 2019 for the six laboratories as presented in Fig 2.
(XLSX)

S3 Table. Summary of the information on the satellite Infrastructure considered for the six OMP laboratories. The table contains all the necessary information to solve the Eq 1 in the text, which includes both the data required to estimate the carbon footprint of each satellite mission and the results of bibliometric queries to determine the relative share of this footprint to be attributed to each of the six laboratories.
(XLSX)

S4 Table. Summary of the information about IODP and PIRATA expeditions, allowing to constrain fuel use as well as other contributions to the global carbon footprint of the infrastructure (flights, freight, equipment).
(XLSX)

S1 Text. Detailed methodology for the estimation of the carbon footprint of specific sources.
(DOCX)

S2 Text. Extraction of the global share of infrastructure usage for a given laboratory based on bibliometric queries on the Web of Science, Science Explorer and specific infrastructure publication databases.
(DOCX)

S3 Text. The carbon footprint of flights associated with IODP expeditions.
(DOCX)

S4 Text. The fuel use and carbon footprint of the PIRATA infrastructure.
(DOCX)

S5 Text. The fuel use and carbon footprint of a mission to the French Southern and Antarctic Territories with the Marion Dusfresnes.
(DOCX)

S6 Text. Preliminary information on the carbon footprint of the Sea Surface Salinity observatory at LEGOS.
(DOCX)

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Open Research

Data relevant to the carbon footprint of IRAP is available from [17,31]. Data concerning emission factors is publicly available from [35] and [34]. Data concerning activity and publications for the IAGOS, PIRATA and IODP infrastructures is publicly available online at [40–44]. Data concerning satellite missions characteristics is available from online as summarized in S3 Table. Other estimates of carbon footprint derived from aggregated laboratory activity data and infrastructure data are available through the S2–S4 Tables which are also available online at https://zenodo.org/records/13928353.

However, detailed financial listings of purchased or travel listings are not provided due to legal restrictions. These listings disclose the financial and travel data of the studied research laboratories and belong to the laboratories' institutions which establish the secret of financial and economic information (for more information, please contact dgdr.secretariat@cnrs.fr).

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

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