Purchases dominate the carbon footprint of research laboratories

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Abstract

Despite increasing interest for the carbon footprint of higher education institutions, little is known about the carbon footprint associated to research activities. Air travel and attendance to conferences concentrate recent data and debates. Here we develop a hybrid method to estimate the greenhouse gas emissions (GHG) associated to research purchases. To do so, we combine macroeconomic databases, research-centered companies footprints and life-cycle analysis to construct a public database of monetary emission factors (EF) for research purchases. We apply such EFs to estimate the purchases emissions of a hundred of research laboratories in France, belonging to the Labos 1point5 network and gathering more than 20000 staff, from all disciplines. We find that purchases dominate laboratory emissions, with a median of 2.3 tCO_2 e/pers, accounting for more than 50% of emissions, and 3-fold higher than the separate contribution from travel, commutes and heating. Electricity emissions are 5-fold lower in our dataset of laboratories using low carbon electricity but they become preponderant for high carbon electricity mixes (3.5 tCO_2 e/pers). Purchases emissions are very heterogeneous among laboratories, but are strongly correlated with budget, with an average carbon intensity of 0.33 ± 0.07 kg CO_2e/€ and differences between research domains. Finally, we quantify the effect of a series of demand-driven mitigation strategies obtaining a maximum reduction of 20 % in total emissions (-40 % in purchases emissions), suggesting that effectively reducing the carbon footprint of research activities calls for systemic changes.

Introduction

Planetary limits refer to the ensemble of physical, ecological and social constraints that limit the flux of matter and energy sustaining human societies.[1] They have been a subject of continuous discussion for at least two centuries.[2–8] This has spurred the necessity for implementing a material accountability, complementary to a monetary one, in order to curb material and energy flows associated to human activities.

Universities and research laboratories have greatly contributed and continue to actively contribute to a better understanding of these planetary limits, in particular concerning global warming[9] and biodiversity loss.[10] However, research itself has undesired impacts, both directly by consuming natural resources and generating waste and greenhouse gases (GHG)[11] and indirectly through the discovery of processes and techniques that may increase the overall impact of humanity on the environment in the long run.[12–14]

Awareness of the direct impacts of academic research on the environment, and more specifically, on global warming, is illustrated by the steady increase in the scientific literature on the carbon footprint of academic research and higher education.[15] In order to quantify GHG emissions in research, two main approaches have been followed: a top-down and a bottom-up approach. In the former, the carbon footprint of whole universities was estimated using aggregated data from entire institutions, in general without distinguishing research and educational activities.[15–18] In the latter, the footprint of individual and specific research activities such as attending conferences or a PhD project,[19] scientific events such as international conferences[20] or disciplines,[21,22] were assessed.

The large majority of the footprints estimated by higher education institutions focuses on direct and energy-related emissions[15,18] (scope 1 and 2[23]) and only partially includes scope 3 emissions,[24] i.e. those resulting from activities that occur in locations that are not owned by the institution. They are the most diverse and therefore, the most difficult to assess, which explains why they are rarely accounted for. Yet, scope 3 emissions, and among them, purchases of goods and services, can represent a large share of their total footprint.[16,25,26] Some studies suggest that they may account for as much as 80% of total emissions.[17,27]

In this work, we have taken an intermediate approach and selected the research laboratory as a valuable perimeter to evaluate the carbon footprint of research activities. Within this boundary we first propose a method to estimate the carbon footprint of all the goods and services purchased in the laboratory. We construct a public listing of monetary emission factors (EFs) associated to 1431 categories of scientific purchases and 61 physical emission factors associated to 8 labware categories using different databases and complementary methods to assess the robustness of our approach. These EFs can be used as is or through the web interface GES 1point5[28] to calculate the GHG emissions of laboratory purchases. We then compare the different emission sources from 167 carbon footprints associated to 108 distinct French laboratories from all disciplines and show that purchases represent 50% of median emissions. Emissions in general and purchases emissions in particular are very heterogeneous between laboratories and research domains. Interestingly, we find a strong linear correlation between purchases emissions and budget with a carbon intensity of ~ 0.3 kg CO_2e/€ for sciences and technology and life and health sciences laboratories and ~ 0.2

kg CO_2e/ € for human and social sciences laboratories. We conclude by discussing potential mitigation strategies, highlighting the difficulty of reducing purchase-associated emissions in certain disciplines.

Results and discussion

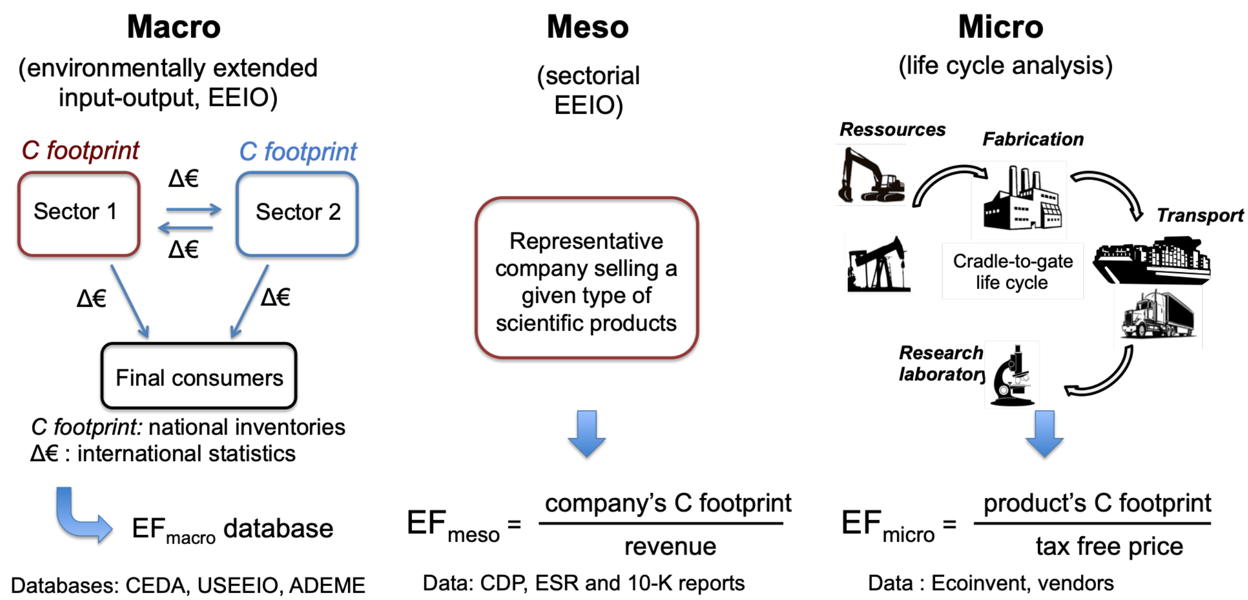

Figure 1: Scheme showing the three approaches used in this work to estimate monetary emission factors (EF) of purchased goods and services.

Emissions embodied in goods and services, can be estimated by measuring physical or monetary flows. To make the problem tractable considering the large number of purchase types in research laboratories, goods were classified according to the French system for accountability in research (NACRES), to which we manually associated cradle-to-gate monetary emission factors (EFs) in kg CO_2e/€. Throughout the text all € values correspond to year 2019. The emissions of good i were calculated as $e(i) = p(i) \times EF(i)$, with $p(i)$ its price in €. EFs were estimated using the three approaches sketched in Fig. 1: i) an environmentally extended input-output (EEIO) method[29] that we will call in the following *macro* and note EF_{macro}; ii) a process-based method that we will call in the following *micro* (EF_{micro});

and iii) an intermediate approach based on the carbon intensity of selected companies of the research sector, that we will called in the following *meso* (EF_{meso}).

Environmentally extended input-output (EEIO) methods associate environmental impacts to macroeconomic monetary flows between production and consumption sectors in a given economy or territory.[29] They have proven useful to estimate the carbon footprint of purchases in large organizations.[30] However, they should be used with caution when applied to niche products which are abundant in research laboratories. We therefore used a hybrid approach: for purchase categories most specific to research labs (scientific instruments and consumables), we completed the EEIO method by our meso and micro approaches.

Construction of the emission factor database

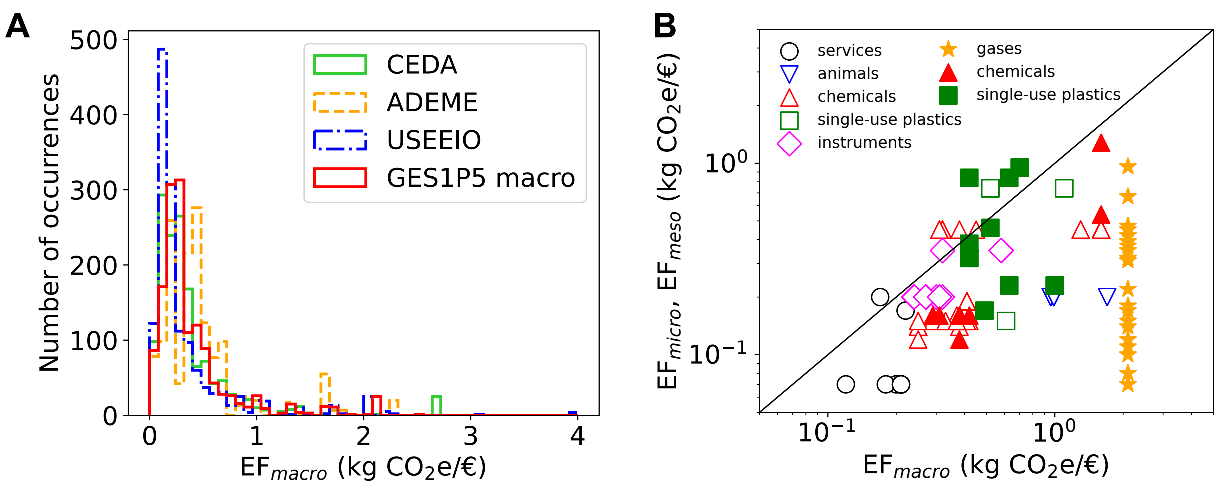

Figure 2: Construction of the GES1P5 NACRES-EF database for estimating the carbon footprint of research laboratories. A) Distribution of macro emission factors within the four macro NACRES-EF databases considered in this work. The y axis represents the number of NACRES codes assigned to a given EF among the 1431 NACRES codes within the purchases module in GES 1point5. B) Meso (open symbols) and micro (filled symbols) emission factors vs. GES1P5 macro EF for different types of purchases.

In a first step, each of the 1431 NACRES categories identifying goods and services was attributed one or several EFs from each one of three EEIO databases: the two American

CEDA[31] and USEEIO[32,33] databases, and the French ADEME[34] database, the first two providing 430 EFs and the last one 38. This constituted three databases of NACRES monetary EFs, called in the following CEDA, USEEIO and ADEME, respectively. In a second step, the GES1P5 macro database was constructed by averaging, for each NACRES category, the EFs from the three other databases. Fig. 2 and Tab. 1 show the properties of the distribution of EFs associated to the different NACRES categories for the four macro databases. Lower EFs are more frequent in the USEEIO database, then comes the CEDA and then the ADEME database with respectively medians of 0.19, 0.27 and 0.40 kg CO_2e/€. The GES1P5 macro database displays a mean EF that is indeed the average of the means of the other three, with a distribution very similar to the CEDA one although without the very high values (Fig. S2).

Table 1: Statistics of the distribution of emission factors (EF) within each NACRES-EF database and of purchases carbon intensities within the GES 1point5 lab emission database for the five NACRES-EF databases used in this work. All the quantities are in kg CO_2e/€ and s.d. is the standard deviation.

	EF			**Carbon intensity (I)**		
NACRES-EF database	**Mean**	**Median**	**s.d.**	**Mean**	**Median**	**s.d.**
USEEIO	0.33	0.18	0.45	0.29	0.28	0.09
CEDA	0.37	0.25	0.42	0.34	0.34	0.08
ADEME	0.47	0.40	0.41	0.43	0.44	0.10
GES1P5 macro	0.39	0.27	0.38	0.35	0.35	0.08
GES1P5 final	0.33	0.24	0.28	0.31	0.30	0.07

In a third and final step, the GES1P5 macro was refined by substituting macro EFs by meso or micro EFs. Meso EFs were computed by calculating the carbon intensity of 14 companies providing representative instruments, consumables and/or services to research labs (Tabs. 2 and S4-S2). Similarly to corporate emissions in other industrial sectors, companies' EF_{meso} most heavily depend on the emissions related to purchased goods and services, that represent 41 to 80% of their total emissions (Tab. S2). These 14 EF_{meso} were attributed to 102 NACRES categories (Tab. S1), with a median of 0.2 kg CO_2e/€, which is close to the median EF of the USEEIO database. Micro EFs were computed using cradle-to-gate single-impact life cycle assessments[35] (LCA) of 60 simple products that constitute a significant purchase amount in at least one discipline, mostly disposable plastic labware and gas cylinders (Tab. S3) and averaged by NACRES category to obtain 36 EF_{micro}.

Table 2: Meso carbon intensities (corporate direct and upstream emissions divided by total sales) of companies whose main clients are research laboratories, aggregated by business segment. Details by company are given in Tabs. S4-S2. Data calculated from 36.

Business segment	**Carbon intensity (kg CO2e/€)**
Gloves and hygienic equipment	0.74
Chemicals	0.45
Global lab supplier (Instrumentation, consumables & services)	0.13 – 0.38
Scientific equipment (> 80% of sales)	0.18 – 0.35
Biotech consumables	0.14 – 0.16
Scientific services	0.07 – 0.19

Fig. 2B shows the correlation between micro/meso EFs and macro ones. For a given category, on average, EF_{meso} are of the same order of magnitude than EF_{macro}, but globally 2-fold lower. The difference is even more important for companies producing chemicals and animals for research, whose sector of activity was not represented in the EEIO databases. For categories corresponding to single-use plastics, with a single exception, EF_{micro} were close to EF_{macro} (less than a 2-fold difference). However, EF_{micro} were much lower than EF_{macro} for chemicals, laboratory glassware and especially gas cylinders. This most probably reflects the small packaging of gases for laboratories compared to industries, resulting in much higher prices per kg of gas. With some exceptions (see methods), these micro and meso EFs were then incorporated into the GES1P5 macro database to constitute the GES1P5 final database. 9 % of EFs were changed (7% with meso EFs and 2% with micro EFs), which accounted for a mean of 12% of lab purchases (in €), with high disparity from one lab to another (from 0 to 53% of all purchases). Despite this small number of changes (Fig. S3), the use of the GES1P5 final database resulted in a 17% decrease of the average carbon intensities within all submissions compared with emissions calculated with the GES1P5 macro database (Tab.

1 and Fig. 3).

The distribution of carbon intensities in the laboratory research economy

To gather financial purchase data from French laboratories to estimate their purchase emissions we relied on GES 1point5,[37,38] an online, free, open source tool developed by the Labos 1point5 network.[39] We created a purchases module that allowed volunteer laboratories to upload their expenses associated to NACRES categories. Interestingly, GES 1point5 allows laboratories to estimate other emission sources such as scope 1 (owned vehicles, cooling gases), scope 2 (electricity and heating) and scope 3 (travels, commuting and computer devices) associated emissions. We designed the purchases module to avoid double counting with the emissions taken into consideration by the other modules. 108 laboratories submitted 167 GHG purchases footprints for different years (mostly 2019).

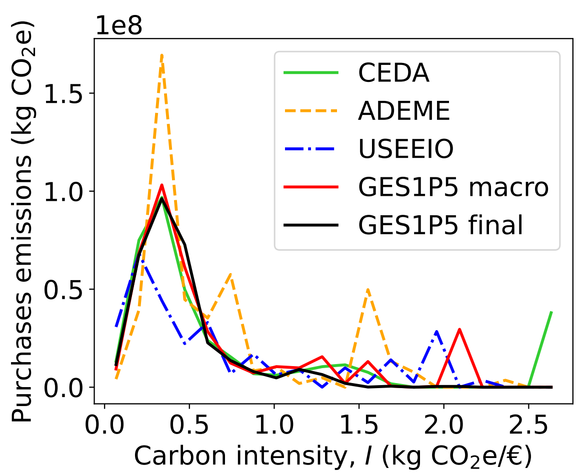

Figure 3: Distribution of carbon intensities within the GES 1point5 laboratory emission database for the five NACRES-EF databases. n = 167 GHG submissions, 108 distinct laboratories, years 2018-2022.

Figs. 3 and S6 show the distribution of carbon intensities I in the 'research laboratory economy' captured by our data. Carbon intensities are weighted by the associated purchases emissions from all laboratories calculated for the five NACRES-EF databases considered here. CEDA and GES1P5 macro provide similar distributions with averages $\bar{I}$ of 0.34 and 0.35 kg CO2e/€ respectively (Tab. 1). GES1P5 final ressembles CEDA and GES1P5 macro for $I < 1.0$ but it results in lower emissions at higher intensities which results in a lower $\bar{I}$ of 0.30 kg CO2e/€. USEEIO and ADEME provide extreme distributions with the former attributing lower emissions for low I ($I < 0.6$) and higher emissions for high I ($I > 1.5$), which yields $\bar{I} = 0.28$ kg CO2e/€, and the later displaying three significant peaks at 0.4, 0.7 and 1.6 kg CO2e/€, associated with a higher mean carbon intensity ($\bar{I} = 0.43$ kg CO2e/€). These results highlight the interest of using different NACRES-FE databases to estimate purchases emissions as we can evaluate, at least partially, the incertitudes of the results. We conclude that the average carbon intensity of laboratory purchases is in the range $0.22 - 0.42$ kg CO2e/€, or 0.32 ± 0.10 kg CO2e/€. This implies that the purchases emissions aggregated for all laboratories is estimated with a precision of 30 % by just multiplying the purchases budget by this average carbon intensity.

Purchases and electricity dominate laboratory emissions

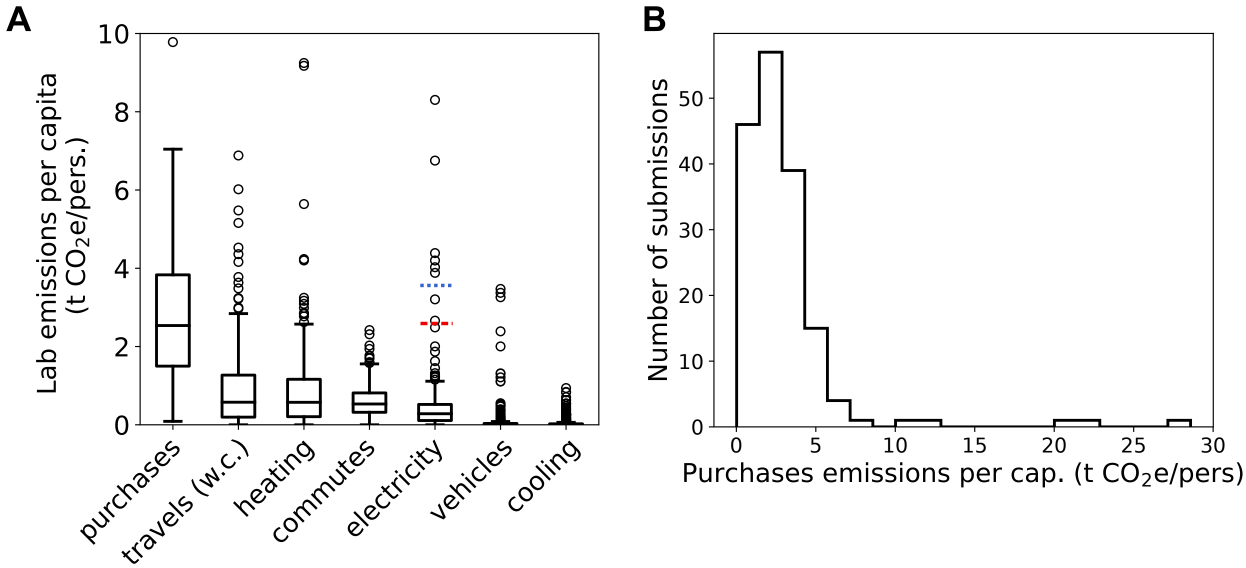

Figure 4: Purchases dominate GHG emissions among laboratories using low-carbon electricity. A) Boxplot of laboratory emissions per capita per emission source. $n = 312$ for all types except for purchases ($n = 167$). w.c. indicates that emissions associated to plane transportation were calculated with contrails.[37] Electricity emissions are calculated for three different mixes: French mix (boxplot in black), world mix (median as a dashed red line), and high-carbon mix (median as dotted blue line). Note that the y axis is truncated (see Fig. S8 and panel B). 203 distinct laboratories. B) Distribution of purchases emissions per capita. Purchases emissions calculated with the GES1p5 final NACRES-FE database. $n = 167$ GHG submissions, 108 distinct laboratories, years 2018-2022.

We now have a robust method to estimate laboratory purchases emissions and in the following we will use solely GES1P5 final FEs to calculate them. An important question is the relative importance of each emission source as this conditions where the efforts of reduction need to be concentrated. Fig. 4A and Tab. S6 display the distribution of emissions for the eight types of emission sources in the GES 1point5 lab emission database. Importantly, this perimeter includes all upstream and in-house laboratory emissions except those due to heavy investments (such as construction and large scientific infrastructures) and staff meals. This database contains more than 300 GHG emission inventories from more than 200 laboratories employing more that 40000 staff, except for purchases for which more than 160 inventories from more than 100 different laboratories and employing more than 23000 staff were available

(Tab. S5). Median laboratory emissions are dominated by purchases with 56% of the share and a median of 2.5 t CO_2e/pers. Travels, heating and commuting to work are far weaker with 12-13% and a median of 0.5-0.6 t CO_2e/pers. Electricity (6%, 0.3 t CO_2e/pers.) comes next, with electricity being particularly low in our dataset due to the low carbon emissions of the French electricity system (60 g CO_2e/kWh[40]). Emissions associated to lab-owned vehicles and cooling systems are negligible on average. Laboratory emissions are however very heterogeneous and the distributions of per capita emissions per source are wide, as shown in Fig. 4B for purchases, with quartiles (1.5, 3.8) t CO_2e/pers and extreme values of $0.09 - 29$ t CO_2 e/pers.

However, to compare these data internationally we need to correct by the carbon intensity of the electricity mix used by the laboratory. The average carbon intensity of the world electricity mix is 7.9-fold higher (475 g CO_2e/kWh[41]), while the highest electricity intensities can be up to 11.7-fold higher (700 g CO_2e/kWh[42]). In these cases the median of electricity emissions either equals purchases emissions per capita (2.4 t CO_2e/pers) or becomes preponderant (3.5 t CO_2e/pers).

Purchases emissions are correlated to budget and research domain

Fig. 5 shows that purchases emissions are strongly correlated to purchases budget with variations by research domain. Laboratory budgets in our database spanned $2 \times 10^3 - 8 \times 10^6$ € with a symmetric distribution of carbon intensities of mean 0.33 kg CO2e/€ and a s.d. of 0.07 CO2e/€. Human and social sciences (HSS) laboratories displayed significantly lower carbon intensities (0.20±0.04 kg CO2e/€) while support laboratories, i.e. large experimental platforms that provide analysis services, display larger carbon intensities associated to a wider distribution (0.4 ± 0.1 kg CO2e/€, Tab. 3). Science and technology (ST) and life and health science (LHS) laboratories were associated to carbon intensities close to the mean (0.32 and 0.30 kg CO2e/€, respectively), with however a tendency of ST laboratories with high budgets to display slightly higher intensities. In contrast, the correlation between emissions and number of staff was weaker (Fig. S9).

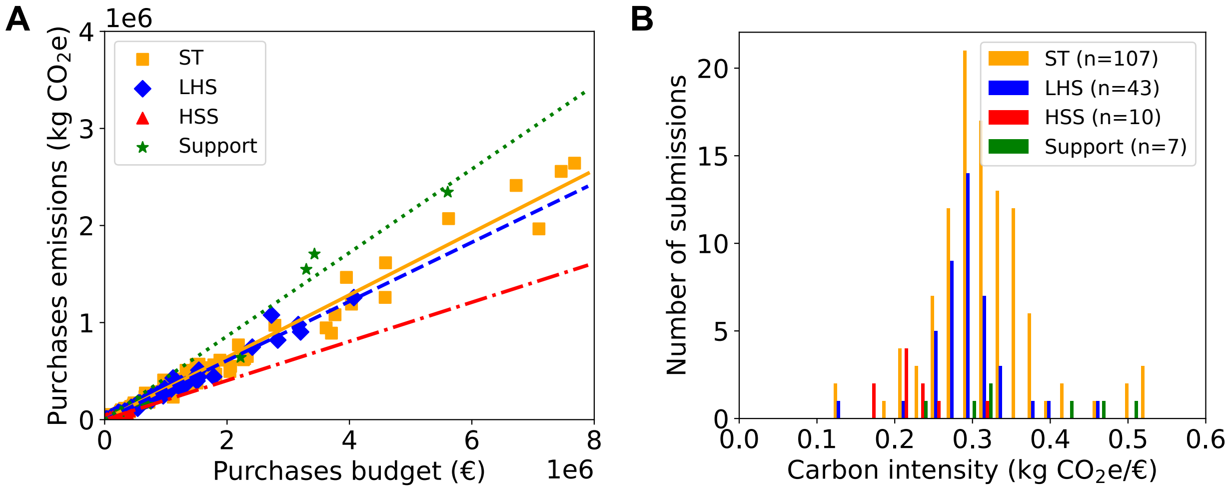

Figure 5: Purchases emissions are proportional to budget, with differences between research domains. A) Purchases emissions vs. budget for all GHG laboratory footprints in the GES 1point5 lab emission database. Lines are linear fits with zero intercept, whose results are provided in Tab. 3. B) Histogram of purchases carbon intensities for different scientific domains. HSS: Human and social sciences, LHS: Life and health sciences, ST: Science and technology. $n = 167$ GHG submissions, 108 distinct laboratories, years 2018-2022.

Table 3: Linear fits of purchases emissions vs. purchases budget for different domains in Fig. 5A.

Domain	Slope (kg CO_2e/€)	R^2
Sciences and technology (ST)	0.32	0.97
Life and health sciences (LHS)	0.30	0.97
Human and social sciences (HSS)	0.20	0.96
Support	0.43	0.96
All	0.33	0.96

The typology of purchases emissions depend on research domain

We classified purchases into seven categories: consumables, IT, lab instruments, repairs & maintenance, services, transport & hosting not included in travel and commuting, and laboratory life (see SI Methods). The share of emissions for these categories strongly depended on the research domain of the laboratory (Fig. 6A). For ST laboratories, purchases emissions are dominated by the acquisition of laboratory instruments (37 ± 23 %), while for LHS consumables dominate (35 ± 18 %). HSS laboratories exhibit a clearly different typology with three categories with shares close to 30% of emissions: IT, services and laboratory life. Weaker but still important contributions for ST laboratories are laboratory life, IT, consumables and services, while for LHS laboratories these are instruments, laboratory life, IT and services. Emissions associated to hosting during travels and to repairs and maintenance represent 5% or less of the purchases footprint.

Such differences imply that mitigation strategies should consider the scientific specificity of the laboratories. At the scale of a single laboratory, our method allows a finer view of the distribution of emissions among different purchases subcategories (Fig. S10). However, one must keep in mind that the financial categorization used here to identify purchases (NACRES) does not allow to distinguish between similar goods with potentially different carbon footprints, thus jeopardizing the estimation of supply-driven mitigation strategies, i.e. decreasing the emission factors.

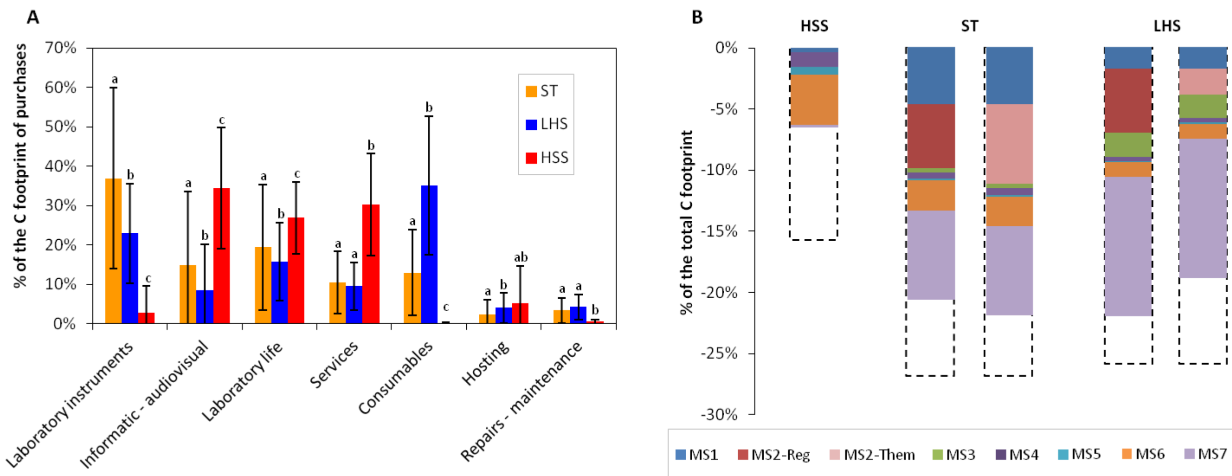

Figure 6: Typology of purchases emissions and quantification of mitigation strategies. A) Share of purchases emissions per research domain (colors) broken down by purchases category. Error bars correspond to one standard deviation and letters indicate significant differences ($p < 0.05$). B) Relative reduction of the total carbon footprint by research domain expected within the GES 1point5 lab emission database for the seven mitigation strategies considered. MS1: +50% of lab equipment life-time; MS2: 50% pooling of lab equipment, either by region (-Reg) or by research sub-discipline (-Them); MS3: replace 80% of plastic by glass; MS4: 75% conversion to vegetarianism; MS5: −50% in furniture purchases; MS6: −50% in informatic purchases; MS7: −50% in consumable purchases. Dotted rectangles correspond to −50% in the purchases footprint. ST: science and technology ($n = 107$), LHS: life and health sciences ($n = 43$), HSS: human and social sciences ($n = 10$) laboratories.

Identifying and quantifying mitigation strategies for scientific purchases

Despite these limitations, it is possible to evaluate the effect of demand-driven mitigation strategies that involve reducing the purchase of certain items. We considered seven of such strategies applied to the three scientific domains (Fig. 6B) and we quantified their relative effect compared to the total carbon footprint of the laboratory (and not just the purchases footprint). Two mitigation strategies addressed scientific equipment: a 50% increase in equipment service life (MS1) and the pooling of 50% of equipments either by sub-discipline (MS2-Them) or by region (MS2-Reg). Two strategies focused on laboratory-life purchases: a 75% conversion of laboratory-paid catering to vegetarianism (MS4) and a 2-fold reduction in furniture purchases (MS5). Two strategies concerned consumables: replacing 80 of plastic consumables by glass (MS3) and reducing 50% all consumables purchases (MS7). Finally, we considered the effect of reducing by 50% IT purchases (MS6). As expected from Fig 6A, the impact of these strategies was relatively similar for ST and LHS laboratories and different for HSS ones. For ST, the most effective strategies concerned reducing consumables (MS7), the pooling of instruments by sub-discipline (MS2-Them), increasing equipment life-time (MS1) and reducing IT (MS6). For LHS MS7 was also the most effective but instrument pooling by region (MS2-Reg) was preferred over MS2-Them, then came replacing plastic by glass in agreement with ref. 43 (MS3) and increasing life-time (MS1). Reducing furniture and conversion to vegetarianism was negligible for both domains. For HSS reducing IT purchases was the most effective, followed by conversion to vegetarianism. The addition of all seven strategies reduced by $\sim$ 40% the footprint associated to purchases and thus by $\sim$ 20% the total footprint, i.e. 1.3 t CO_2e/pers. on average, both for ST and LHS laboratories. In contrast, for HSS, the purchases footprint reduction was $\sim$ 20% and the total one was $\sim$ 6%, i.e. 0.2 t CO_2e/pers. on average. We conclude that demand-driven mitigation strategies may be very effective to reduce the carbon footprint of both ST and LHS laboratories.

Discussion and conlusion

Purchases emissions are almost systematically neglected[15,18,25] when calculating the carbon footprint of higher education institutions, except in few seminal studies.[16,17,44] However, these works do not separate research and teaching activities, they only analyze a single institution and use a single set of monetary EFs. The average carbon intensity calculated by Larsen et al. for a Norwegian technical university,[16] 0.39 kg CO2e/€ 2019, is close to the one calculated here for a French database of more than hundred different laboratories (0.33 ± 0.07 kg CO2e/€ 2019). Interestingly, however, Larsen et al did not find significant differences in the carbon intensities between research domains (Tab. S7), in particular with HSS, in contrast to the current work. We thus hypothesize that the distinction between research and teaching activities is important because the heterogeneity of purchases emissions found in our data suggest that mitigation strategies will need to be adapted to each laboratory. However, the results obtained for HSS laboratories need to be considered with caution because only 10 footprints from 8 distinct laboratories were available in the GES 1point5 laboratory emission database.

In addition, available data of purchases footprints in universities rely on either non-public EF[16] or general-economy EEIO EF databases such as EXIOBASE,[45] thus not offering a general method for research laboratories. Our results indicate that the NACRES-EF database allows to calculate laboratory purchases emissions with a 20% precision, although further work needs to be done to refine emissions associated to laboratory instruments. In addition, previous works do not show the great heterogeneity of emissions among research laboratories, both between different emission sources and within purchases alone. Importantly, our data suggest that laboratory budget is the main driver of purchases emissions, in a similar way as income determines the carbon footprint of households.[46]

The strong linearity observed between purchases emissions and budget in Fig. 5A is intriguing. On the one side, one may argue that this linearity is consubstantial to a model using monetary EFs, and thus it is not a result per se. On the other hand, the distribution of carbon intensities in our data (Figs. 3 and 5B) is relatively large, and thus suggests that both the linearity and the differences in the carbon intensities observed between domains are a result and not an artefact of our model.

The monetary and aggregated approach that we have followed in this study does not allow evaluating mitigation strategies coming from choices of consumables or instruments with lower carbon footprint than their classical counterparts (supply-based strategies). Such mitigation strategies must be subject to specific estimates based on physical factors and data from suppliers. The difficulty of these mitigation strategies is that they require precise determination of the carbon footprints of one type of product from different manufacturers (or of different models of the same supplier). Few data exist for convenience goods that are part of lab purchases such as computers or printer toners. But for most laboratory equipment an additional difficulty is that they are made up of components manufactured in very small series, and LCA databases contain only data on mass-produced products that have high production costs relative to overhead. In consequence, precise process-based carbon footprints are so far inexistent for laboratory equipments or specific consumables, limiting the possibility to evaluate mitigation strategies based on supplier specific processes for labs. Concerning the monetary factor approach, it should be noted that on the long term, general decarbonation of industry worldwide should reflects on decrease of EF monetary ratios.

Methods

Classification of goods and approach

Services and goods purchased in a laboratory are classified according to the French NACRES nomenclature, used in the accountability of the majority of research institutions in France.[47] Each type of good or service is identified by a code composed of two letters and two numbers. The first letter provides the general category of the purchase, the second letter designs the domain, the first number the sub-domain and the last number the type. There are 1431 defined types split into 24 large categories (Tab. S1). In this work, each NACRES code is given an EF covering GHG emissions associated to all stages of its production (cradle-to-gate perimeter). Each NACRES code is given an EF using the *macro* method (see below), and certain types of goods were also attributed a meso or a micro EF (see below), that were used to construct a final hybrid database. This final database contained 1281 macro, 108 meso and 43 micro EFs (Tab. S1). Complete methodology is described in the SI file.

The macro approach

To associate EFs with each NACRES code while having an uncertainty estimate, we used three different EEIO databases of monetary emission factors: the French *Ratios Monétaires* database published by the *Agence De l'Environnement et de la Maîtrise de l'Energie* (ADEME)in 2016; the U.S. CEDA[31] database provided by Vitalmetrics (version 4.8 released in 2014); and the U.S. USEEIO[32,33] compiled by the US Environmental protection agency (EPA, published in 2018). Both American databases contain approximately the same 430 categories, while the French ADEME database provides monetary factors for only 38 categories.[34] As the NACRES types cannot always be associated to a single category of the EEIO databases, we associated up to 2 ADEME EFs and up to 6 CEDA/USEEIO EFs to each NACRES category (Tab. S1). We proceeded heuristically by attempting to assign all the EEIO categories of commodities that have similarities (in terms of composition and/or manufacturing process) with the products comprised in each NACRES type. To provide a single EF for each NACRES we averaged the allocated EFs, first within each database, and then between databases. For each EF we calculated uncertainties using two methods. First, attribution uncertainties were computed as the standard deviation of the averaging within databases and across databases. Second, a uniform relative uncertainty of 80% was attributed to all EF. For calculating the footprint of a single laboratory we recommend to use the 80% uncertainty. However, for the results displayed in this work, EF uncertainties did not play any role.

The meso approach

To consolidate macro NACRES-FE database, we used a supplier-based approach, using GHG emissions and financial data of companies whose main segments of activity are to manufacture products of provide services to the research, analytical and health markets. We gathered emission data from the Carbon Disclosure Project (CDP)[36] or from internal reports, and financial data from the annual reports of companies. A limitation of this approach is that, in

November 2022, reasonably complete and reliable GHG emissions (including upstream scope 3) were available only for few large companies, listed in Tabs. S4 and S2. The emission categories used encompass all upstream activities involved in the production of goods or services, similarly to the cradle-to-gate perimeter of EEIO databases, but also downstream transportation as most shipment costs are included in prices for laboratory products. The meso monetary EFs are then computed as EF_{meso} = (scope 1+2+3 upstream emissions)/(revenue).

The micro approach

For laboratory mono-material products that represented important purchases from a panel of laboratories, we performed single impact cradle-to-gate LCA. This concerned 60 products distributed in 28 NACRES categories, such as all gases and some plasticware and glassware (Table S3). LCA included raw material manufacturing, item manufacturing and transport to the local supplier. Emission factors of each step were obtained from the Ecoinvent database version 3.8. The product monetary EFs are then computed by dividing the product carbon footprint by its price. More information about the Ecoinvent EFs and prices used is provided in the SI. The micro monetary EF are then computed as the mean of the monetary EFs of all products belonging to the same NACRES category (1 to 6 products by NACRES category).

Data collection and treatment

All data used in this study have been collected with the GES 1point5 web application.[37,38] For this purpose, a new module has been developed and implemented in the existing application. Volunteer French research laboratories submitted their purchase data through GES 1poin5 as a csv file with NACRES codes and the associated tax-free purchase price. Since heating, electricity, commuting, professional travels and computers were already included in GES 1point5 as dedicated modules, each NACRES code has been allocated a tag called 'Module' that can take five different values: PURCHASE, ENERGY, VEHICLES, TRAVEL and COMPUTER. The monetary approach described here is only used to calculate the emissions of the NACRES types labeled PURCHASE. In this work, purchases emissions are the sum of emissions calculated via the purchases module (via monetary EFs) and the computer devices module (via physical EFs) of GES 1point5. However, emissions related to the devices module were negligible compared to those of the purchases module. Emissions related to the other sources are computed differently by the dedicated modules of GES 1point5 with EFs based on physical flows as described by 37.

Data analysis was performed using custom Python routines. The purchases are classified in 7 aggregated categories in order to facilitate the interpretation of the emissions and the identification of action strategies. These categories are *lab.life* (Food, landscaping, leisure, building), *consumables* (Raw materials, chemicals/biologicals and living organisms), *lab.equipment* (Laboratory equipment and instruments), *transport* (professional travel, including lodging but excluding transport), *info* (computers and audio-video equipment), *services* and *maintenance*. Note that the *info* category only includes the NACRES types that are not accounted for in the COMPUTER module of GES1p5 (see the SI for more information). A third tag called 'Poste' indicates for each type the emission category as described in the standard GHG protocol.[23]

Mitigation strategies

Six mitigation strategies (MS) were calculated.

MS1 assumes a 50% increase in the service life of laboratory equipments. The total carbon footprint and the footprint of "equipments" and of "repair and maintenance" were summed by discipline. The footprint of equipments was divided by 1.5 and the footprint of repair and maintenance was multiplied by 1.5.

MS2 assumes a pooling of 50% of laboratory equipments. For the pooling by discipline, the total footprint and the footprint of "equipments" and of "repair and maintenance" were summed by discipline, while for the pooling at the regional scale, the total footprint and the footprint of "equipments" and of "repair and maintenance" were summed by administrative region if at least 9 GHG assessments were available (four regions). The footprint of equipments was divided by 2 and the footprint of repair and maintenance was multiplied by 2. The results at the regional scale are the average of four regions.

MS3 assumes an 80% decrease in the use of disposable plastic consumables (NACRES codes NB02, NB03, NB04, NB11, NB12, NB13, NB14, NB15, NB16 and NB17). It implies an 80% increase in the use of consumables for washing machines (NACRES code NB34). The first year, it also implies an increase in the purchases of glassware (NACRES code NB43; EF = 0.23 ± 0.1 kg CO_2e/€) for an amount equivalent of twice the amount of disposable plastic consumables. From the second year, a 5% breakage was assumed. The total footprint and the footprint of disposable plastic consumables and of consumables for washing machine were summed by discipline.

MS4 assumes a 50% decrease in the purchases of furniture (NACRES code AB.02). The total footprint and the footprint of furniture were summed by discipline. The footprint of furniture was divided by 2.

MS5 assumes a change in diet with an increase in the proportion of vegetarian menu. The total footprint and the footprint of catering services (NACRES codes AA63, AA64) were summed by discipline. According to ADEME, the mean footprint of a traditional meal in France is 2.04 kg CO_2e and the mean footprint of a vegetarian meal is 0.5 kg CO_2e. Assuming a 75 % conversion to vegetarianism, the footprint of catering services was divided by 3.

MS6 assumes a 50% decrease in consumables. Two classes of consumables were considered. The first one was laboratory consumables and corresponded to the category "consumables". The second one was consumables for scientific equipments and was included in the category "laboratory instruments". The footprint of this class of consumables was determined by removing the footprint of equipments to the footprint of the category "laboratory instruments". The total footprint and the footprint of consumables were summed by discipline. The footprint of consumables was divided by 2.

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