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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 hundreds of research laboratories in France gathering more than 20000 staff, from all disciplines. We find that purchases dominate laboratory

12 emissions, with a median of 2.3 tCO₂ e/pers, accounting for more than 50% of emis-
13 sions, and 3-fold higher than the individual contribution from travel, commutes and
14 heating. Electricity emissions are 5-fold lower in our dataset of laboratories using low
15 carbon electricity but they become preponderant for high carbon electricity mixes (3.5
16 tCO₂ e/pers). Purchases emissions are very heterogeneous among laboratories, but
17 are strongly correlated with budget, with an average carbon intensity of 0.33 ± 0.07 kg
18 CO₂e/€ and differences between research domains. Finally, we quantify the effect of a
19 series of demand-driven mitigation strategies obtaining a maximum reduction of 15 %
20 in total emissions, suggesting that effectively reducing the carbon footprint of research
21 activities calls for systemic changes.

22 Introduction

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

28 Universities and research laboratories have greatly contributed and continue to actively
29 contribute to a better understanding of these planetary limits, in particular concerning global
30 warming⁹ and biodiversity loss.¹⁰ However, research itself has undesired impacts, both di-
31 rectly by consuming natural resources and generating waste and greenhouse gases (GHG)¹¹
32 and indirectly through the discovery of processes and techniques that may increase the overall
33 impact of humanity on the environment in the long run.¹²⁻¹⁴

34 Awareness of the direct impacts of academic research on the environment, and more
35 specifically, on global warming, is illustrated by the steady increase in the scientific lit-
36 erature on the carbon footprint of academic research and higher education.¹⁵ In order to
37 quantify GHG emissions in research, two main approaches have been followed: a top-down

38 and a bottom-up approach. In the former, the carbon footprint of whole universities was
39 estimated using aggregated data from entire institutions, in general without distinguishing
40 research and educational activities.^{15–18} In the latter, the footprint of individual and specific
41 research activities such as attending conferences or a PhD project,¹⁹ scientific events such
42 as international conferences²⁰ or disciplines,^{21,22} were assessed.

43 The large majority of the footprints estimated by higher education institutions focuses on
44 direct and energy-related emissions^{15,18} (scope 1 and 2²³) and only partially includes scope
45 3 emissions,²⁴ i.e. those resulting from activities that occur in locations that are not owned
46 by the institution. They are the most diverse and therefore, the most difficult to assess,
47 which explains why they are rarely accounted for. Yet, scope 3 emissions, and among them,
48 purchases of goods and services, can represent a large share of their total footprint.^{16,25,26}
49 Some studies suggest that they may account for as much as 80% of total emissions.^{17,27}

50 In this work, we have taken an intermediate approach and selected the research labora-
51 tory as a valuable perimeter to evaluate the carbon footprint of research activities. Within
52 this boundary we first propose a method to estimate the carbon footprint of all the goods
53 and services purchased in the laboratory. We construct a public listing of monetary emission
54 factors (EFs) associated to 1431 categories of scientific purchases and 61 physical emis-
55 sion factors associated to 8 labware categories using different databases and complementary
56 methods to assess the robustness of our approach. These EFs can be used as is or through
57 the web interface GES 1point5²⁸ to calculate the GHG emissions of laboratory purchases.
58 We then compare the different emission sources from 167 carbon footprints associated to
59 108 distinct French laboratories from all disciplines and show that purchases represent 50%
60 of median emissions. Emissions in general and purchases emissions in particular are very
61 heterogeneous between laboratories and research domains. Interestingly, we find a strong
62 linear correlation between purchases emissions and budget with a carbon intensity of ~ 0.3
63 kg CO₂e/ € for sciences and technology and life and health sciences laboratories and ~ 0.2
64 kg CO₂e/ € for human and social sciences laboratories. We conclude by discussing potential

65 mitigation strategies, highlighting the difficulty of reducing purchase-associated emissions in
 66 certain disciplines.

67 Results and discussion

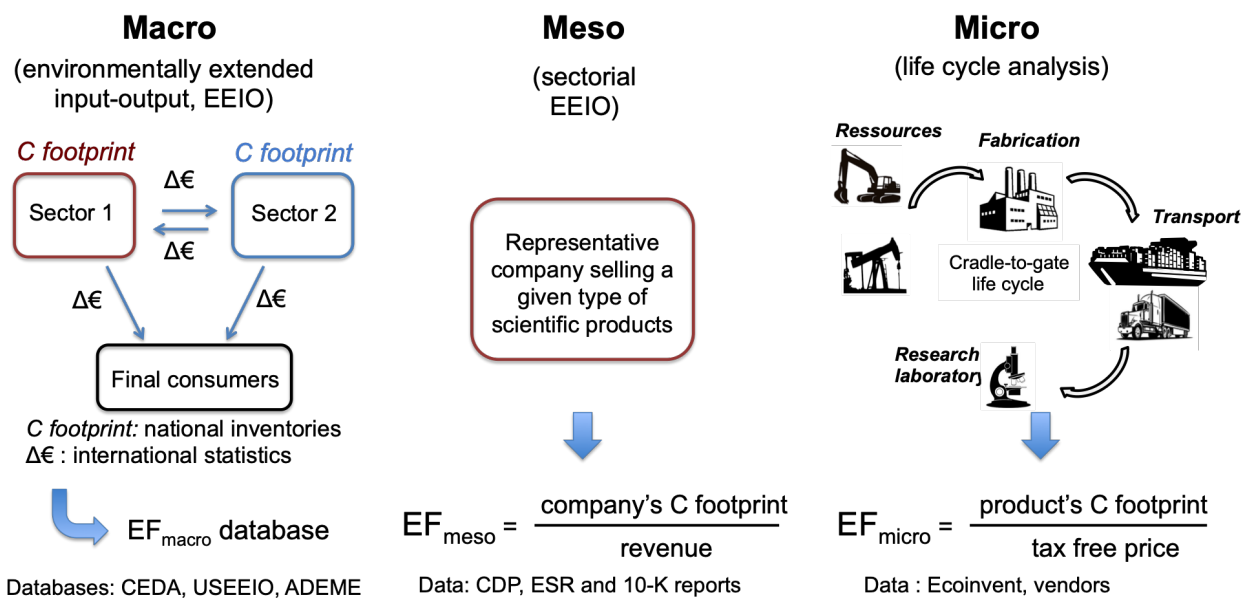


Figure 1: Scheme showing the three approaches used in this work to estimate monetary emission factors (EF) of purchased goods and services.

68 Emissions embodied in goods and services, can be estimated by measuring physical or
 69 monetary flows. To make the problem tractable considering the large number of purchase
 70 types in research laboratories, goods were classified according to the French system for
 71 accountability in research (NACRES), to which we manually associated cradle-to-gate mon-
 72 etary emission factors (EFs) in kg CO₂e/€. Throughout the text all € values correspond to
 73 year 2019. The emissions of good i were calculated as $e(i) = p(i) \times EF(i)$, with $p(i)$ its price
 74 in €. EFs were estimated using the three approaches sketched in Fig. 1: i) an environmen-
 75 tally extended input-output (EEIO) method²⁹ that we will call in the following *macro* and
 76 note EF_{macro} ; ii) a process-based method that we will call in the following *micro* (EF_{micro});
 77 and iii) an intermediate approach based on the carbon intensity of selected companies of the

78 research sector, that we will call in the following *meso* (EF_{meso}).

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

86 Construction of the emission factor database

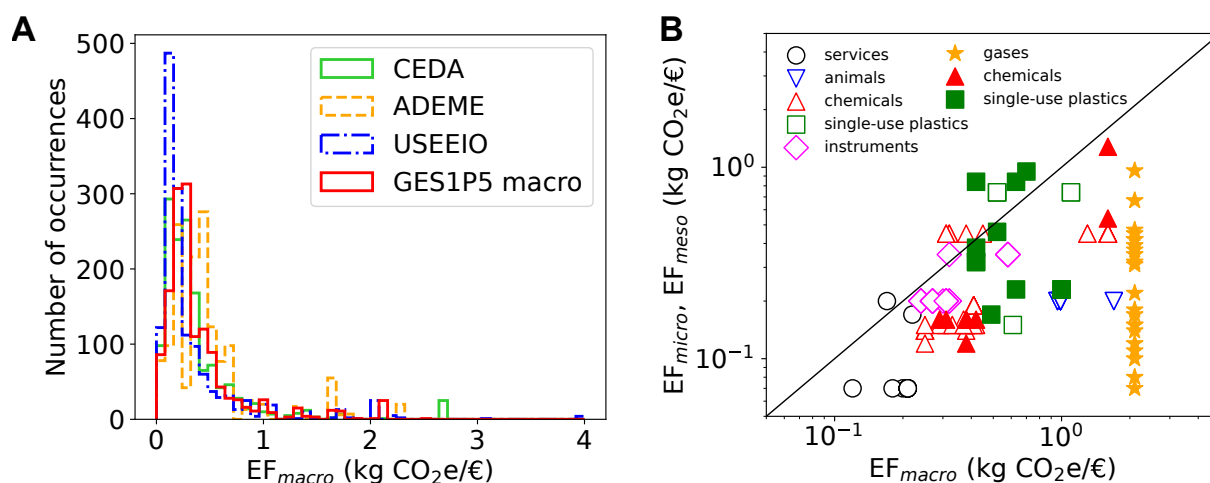


Figure 2: Construction of the GES1P5 NACRES-EF database for estimating the carbon footprint of research laboratories. A) Distribution of macro emission factors within the four macro NACRES-EF databases considered in this work. The y axis represents the number of NACRES codes assigned to a given EF among 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.

87 In a first step, each of the 1431 NACRES categories identifying goods and services was
88 attributed one or several EFs from each one of three EEIO databases: the two American
89 CEDA³¹ and USEEIO^{32,33} databases, and the French ADEME³⁴ database, the first two pro-

90 viding 430 EFs and the last one 38. This constituted three databases of NACRES monetary
 91 EFs, called in the following CEDA, USEEIO and ADEME, respectively. In a second step,
 92 the GES1P5 macro database was constructed by averaging, for each NACRES category, the
 93 EFs from the three other databases. Fig. 2 and Tab. 1 show the properties of the distri-
 94 bution of EFs associated to the different NACRES categories for the four macro databases.
 95 Lower EFs are more frequent in the USEEIO database, then comes the CEDA and then
 96 the ADEME database with respectively medians of 0.19, 0.27 and 0.40 kg CO₂e/€. The
 97 GES1P5 macro database displays a mean EF that is indeed the average of the means of the
 98 other three, with a distribution very similar to the CEDA one although without the very
 99 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 CO₂e/€ and s.d. is the standard deviation.

NACRES-EF database	EF			Carbon intensity (<i>I</i>)		
	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

100 In a third and final step, the GES1P5 macro was refined by substituting macro EFs
 101 by meso or micro EFs. Meso EFs were computed by calculating the carbon intensity of
 102 14 companies providing representative instruments, consumables and/or services to research
 103 labs (Tabs. 2 and S4-S2). Similarly to corporate emissions in other industrial sectors,
 104 companies' EF_{meso} most heavily depend on the emissions related to purchased goods and
 105 services, that represent 41 to 80% of their total emissions (Tab. S2). These 14 EF_{meso} were
 106 attributed to 102 NACRES categories (Tab. S1), with a median of 0.2 kg CO₂e/€, which is
 107 close to the median EF of the USEEIO database. Micro EFs were computed using cradle-

108 to-gate single-impact life cycle assessments³⁵ (LCA) of 60 simple products that constitute a
109 significant purchase amount in at least one discipline, mostly disposable plastic labware and
110 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 CO ₂ e/€)
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

111 Fig. 2B shows the correlation between micro/meso EFs and macro ones. For a given
112 category, on average, EF_{meso} are of the same order of magnitude than EF_{macro} , but globally
113 2-fold lower. The difference is even more important for companies producing chemicals and
114 animals for research, whose sector of activity was not represented in the EEIO databases. For
115 categories corresponding to single-use plastics, with a single exception, EF_{micro} were close to
116 EF_{macro} (less than a 2-fold difference). However, EF_{micro} were much lower than EF_{macro} for
117 chemicals, laboratory glassware and especially gas cylinders. This most probably reflects the
118 small packaging of gases for laboratories compared to industries, resulting in much higher
119 prices per kg of gas. With some exceptions (see methods), these micro and meso EFs were
120 then incorporated into the GES1P5 macro database to constitute the GES1P5 final database.
121 9 % of EFs were changed (7% with meso EFs and 2% with micro EFs), which accounted for
122 a mean of 12% of lab purchases (in €), with high disparity from one lab to another (from
123 0 to 53% of all purchases). Despite this small number of changes (Fig. S3), the use of the
124 GES1P5 final database resulted in a 17% decrease of the average carbon intensities within
125 all submissions compared with emissions calculated with the GES1P5 macro database (Tab.
126 1 and Fig. 3).

127 **The distribution of carbon intensities in the laboratory research**
128 **economy**

129 To gather financial purchase data from French laboratories to estimate their purchase emis-
130 sion footprint we relied on the GES 1point5 web application.^{37,38} We created a purchases
131 module that allowed volunteer laboratories to upload their expenses associated to NACRES
132 categories. Interestingly, GES 1point5 allows laboratories to estimate other emission sources
133 such as scope 1 (owned vehicles, cooling gases), scope 2 (electricity and heating) and scope
134 3 (travels, commuting and computer devices) associated emissions. We designed the pur-
135 chases module to avoid double counting with the emissions taken into consideration by the
136 other modules. 108 laboratories submitted 167 GHG purchases footprints for different years
137 (mostly 2019).

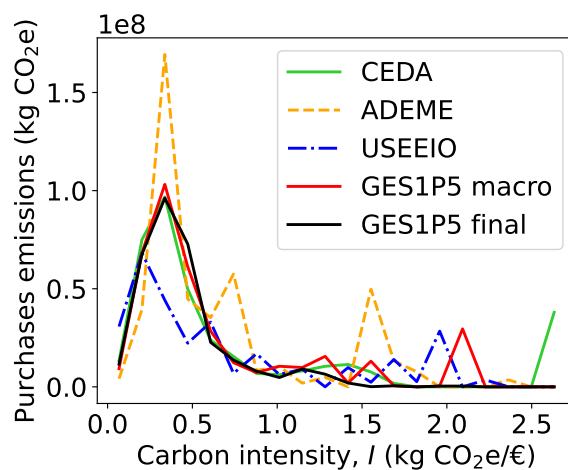


Figure 3: Distribution of carbon intensities within the GES 1point5 laboratory emission database for the five NACRES-EF databases. $n = 167$ GHG submissions, 108 distinct laboratories, years 2018-2022.

138 Figs. 3 and S6 show the distribution of carbon intensities I in the ‘research laboratory
139 economy’ captured by our data. Carbon intensities are weighted by the associated purchases
140 emissions from all laboratories calculated for the five NACRES-EF databases considered
141 here. CEDA and GES1P5 macro provide similar distributions with averages \bar{I} of 0.34 and

142 0.35 kg CO₂e/€ respectively (Tab. 1). GES1P5 final ressembles CEDA and GES1P5 macro
143 for $I < 1.0$ but it results in lower emissions at higher intensities which results in a lower \bar{I}
144 of 0.30 kg CO₂e/€. USEEIO and ADEME provide extreme distributions with the former
145 attributing lower emissions for low I ($I < 0.6$) and higher emissions for high I ($I > 1.5$),
146 which yields $\bar{I} = 0.28$ kg CO₂e/€, and the later displaying three significant peaks at 0.4, 0.7
147 and 1.6 kg CO₂e/€, associated with a higher mean carbon intensity ($\bar{I} = 0.43$ kg CO₂e/€).
148 These results highlight the interest of using different NACRES-FE databases to estimate
149 purchases emissions as we can evaluate, at least partially, the incertitudes of the results. We
150 conclude that the average carbon intensity of laboratory purchases is in the range 0.22 – 0.42
151 kg CO₂e/€, or 0.32 ± 0.10 kg CO₂e/€. This implies that the purchases emissions aggregated
152 for all laboratories is estimated with a precision of 30 % by just multiplying the purchases
153 budget by this average carbon intensity.

154 Purchases and electricity dominate laboratory emissions

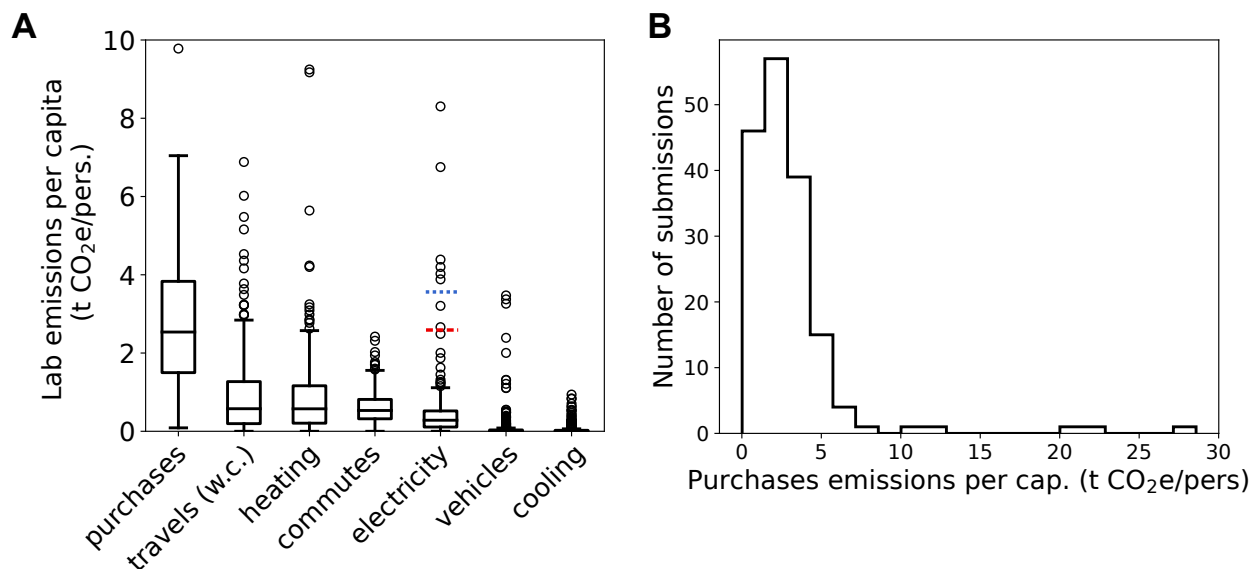


Figure 4: Purchases dominate GHG emissions among laboratories using low-carbon electricity. A) Boxplot of laboratory emissions per capita per emission source. $n = 312$ for all types except for purchases ($n = 167$). w.c. indicates that emissions associated to plane transportation were calculated with 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.

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

165 (Tab. S5). Median laboratory emissions are dominated by purchases with 56% of the share
166 and a median of 2.5 t CO₂e/pers. Travels, heating and commuting to work are far weaker
167 with 12-13% and a median of 0.5-0.6 t CO₂e/pers. Electricity (6%, 0.3 t CO₂e/pers.) comes
168 next, with electricity being particularly low in our dataset due to the low carbon emissions
169 of the French electricity system (60 g CO₂e/kWh³⁹). Emissions associated to lab-owned
170 vehicles and cooling systems are negligible on average. Laboratory emissions are however
171 very heterogeneous and the distributions of per capita emissions per source are wide, as
172 shown in Fig. 4B for purchases, with quartiles (1.5, 3.8) t CO₂e/pers and extreme values of
173 0.09 – 29 t CO₂ e/pers.

174 However, to compare these data internationally we need to correct by the carbon in-
175 tensity of the electricity mix used by the laboratory. The average carbon intensity of the
176 world electricity mix is 7.9-fold higher (475 g CO₂e/kWh⁴⁰), while the highest electricity
177 intensities can be up to 11.7-fold higher (700 g CO₂e/kWh⁴¹). In these cases the median
178 of electricity emissions either equals purchases emissions per capita (2.4 t CO₂e/pers) or
179 becomes preponderant (3.5 t CO₂e/pers).

180 **Purchases emissions are correlated to budget and research domain**

181 Fig. 5 shows that purchases emissions are strongly correlated to purchases budget with
182 variations by research domain. Laboratory budgets in our database spanned $2 \times 10^3 - 8 \times 10^6$
183 € with a symmetric distribution of carbon intensities of mean 0.33 kg CO₂e/€ and a s.d.
184 of 0.07 CO₂e/€. Human and social sciences (HSS) laboratories displayed significantly lower
185 carbon intensities (0.20 ± 0.04 kg CO₂e/€) while support laboratories, i.e. large experimental
186 platforms that provide analysis services, display larger carbon intensities associated to a
187 wider distribution (0.4 ± 0.1 kg CO₂e/€, Tab. 3). Science and technology (ST) and life
188 and health science (LHS) laboratories were associated to carbon intensities close to the
189 mean (0.32 and 0.30 kg CO₂e/€, respectively), with however a tendency of ST laboratories
190 with high budgets to display slightly higher intensities. In contrast, the correlation between

191 emissions and number of staff was weaker (Fig. S9).

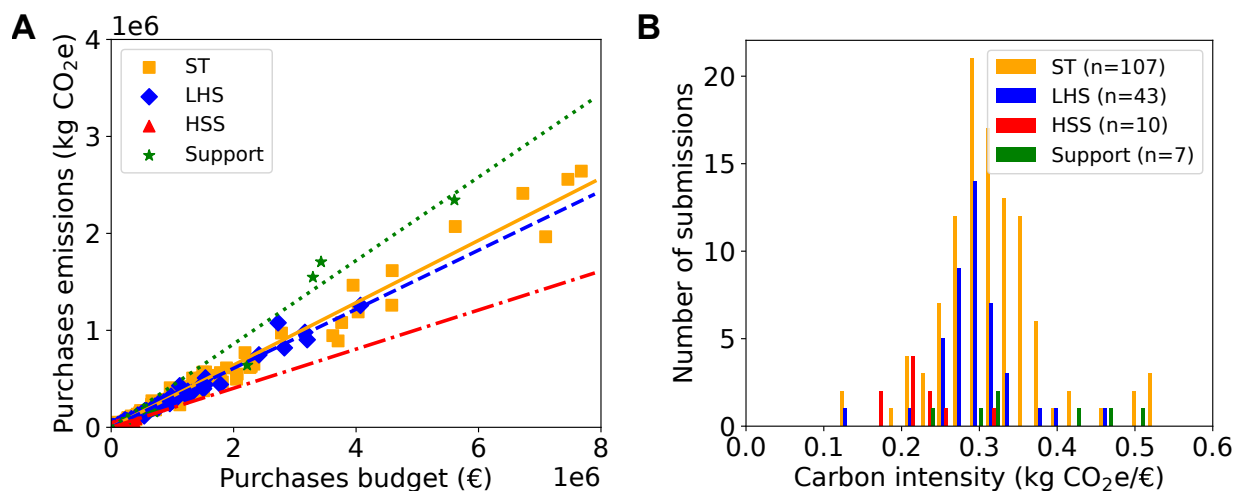


Figure 5: Purchases emissions are proportional to budget, with differences between research domains. A) Purchases emissions vs. budget for all GHG laboratory footprints in the GES 1point5 lab emission database. Lines are linear fits with zero intercept, whose results are provided in Tab. 3. B) Histogram 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 ₂ e/€)	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

192 The typology of purchases emissions depend on research domain

193 We classified purchases into seven categories: consumables, IT, lab instruments, repairs
 194 & maintenance, services, transport & hosting not included in travel and commuting, and
 195 laboratory life (see SI Methods). The share of emissions for these categories strongly de-
 196 pended on the research domain of the laboratory (Fig. 6A). For ST laboratories, purchases

197 emissions are dominated by the acquisition of laboratory instruments ($39 \pm 19 \%$), while
198 for LHS laboratories instruments and consumables have a similar share ($32 \pm 15 \%$ and
199 $26 \pm 13 \%$, respectively). HSS laboratories exhibit a clearly different typology with three
200 categories with shares close to 30% of emissions: IT, services and laboratory life represent
201 $27 \pm 14\%$, $31 \pm 14 \%$ and $32 \pm 9 \%$, respectively. Such differences imply that mitigation
202 strategies should consider the scientific specificity of the laboratories. At the scale of a single
203 laboratory, our method allows a finer view of the distribution of emissions among different
204 purchases subcategories (Fig. S10). However, one must keep in mind that the financial cate-
205 gorization used here to identify purchases (NACRES) does not allow to distinguish between
206 similar goods with potentially different carbon footprints, thus jeopardizing the estimation
207 of supply-driven mitigation strategies, i.e. decreasing the emission factors.

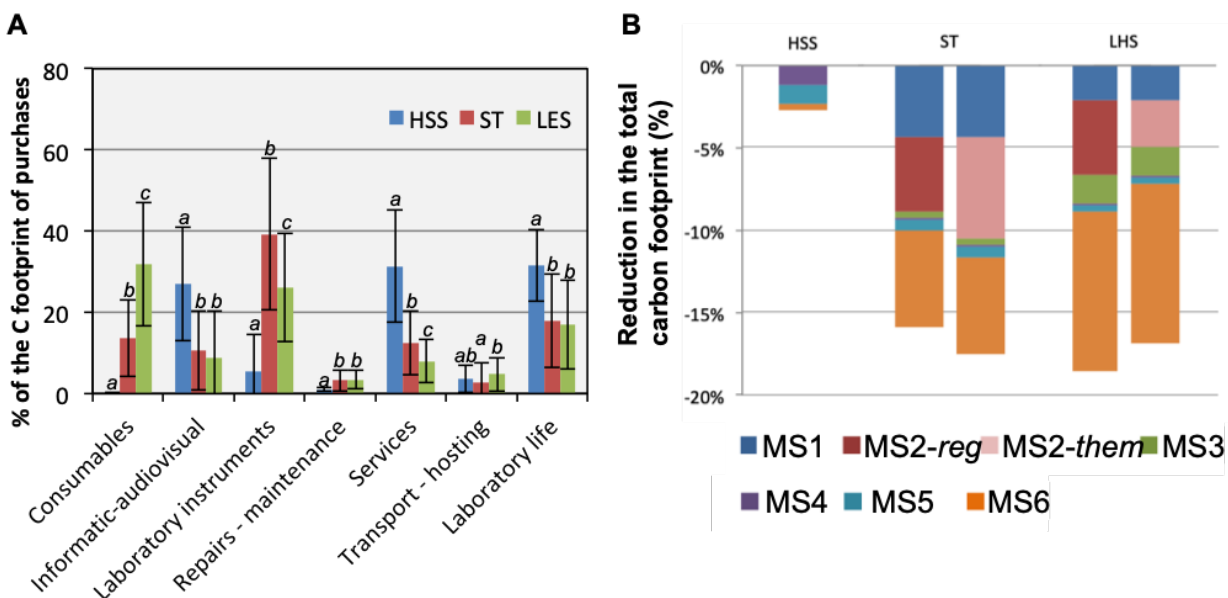


Figure 6: Typology of purchases emissions and quantification of mitigation strategies. A) Share of purchases emissions per research domain (colors) broken down by purchases category. Error bars correspond to one standard deviation and letters indicate significant differences ($p < 0.05$). B) Purchases emission reductions by research domain expected within the GES 1point5 lab emission database for the seven mitigation strategies considered. MS1: 50% increase 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: 50% decrease in furniture purchases, MS5: 75% conversion to vegetarianism. HSS: human and social sciences ($n = 5$), ST: science and technology ($n = 58$), LHS: life and health sciences ($n = 21$) laboratories.

208 Identifying and quantifying mitigation strategies for scientific pur- 209 chases

210 Despite these limitations, it is possible to evaluate the effect of demand-driven mitigation
211 strategies that involve reducing the purchase of certain items. We considered six of such
212 strategies applied to the three scientific domains (Fig. 6B) and we quantified their relative
213 effect compared to the total carbon footprint of the laboratory (and not just the purchases
214 footprint). Two mitigation strategies addressed scientific equipment. The impact of a 50%
215 increase in their service life on purchases emissions (MS1) is higher for ST laboratories
216 (-4.4 ± 3.5 %) than for LHS laboratories (-2.1 ± 1.7 %). The pooling of scientific equipment

217 (MS2) can be performed either at a regional scale or at the national scale by scientific domain.
218 Since this category of purchases was 1.5-fold higher for ST laboratories than for LHS ones,
219 the pooling by scientific discipline induced a higher decrease of purchases footprint in the
220 former (-6.1 ± 4.9 %) than in the latter (-2.8 ± 2.2 %). The impact of the pooling at regional
221 scale resulted in a similar impact for ST and LHS (-4.5 ± 3.6 %). Two other mitigation
222 strategies addressed laboratory-life purchases. In this category, emissions were dominated by
223 furniture and catering. Reducing 2-fold furniture purchases (MS3) allowed a 1.2 % decrease
224 in the footprint of HSS laboratories but only a 0.1 % decrease of ST and LHS laboratories.
225 Increasing the share of vegetarian meals to 75 % in catering services (MS4) reduced by -1.2
226 %, -0.6 % and -0.4 % for HSS, ST and LHS laboratories, respectively. Finally, two strategies
227 addressed the purchases of scientific consumables. Replacing 80 % of disposable plastic
228 consumables with glassware (MS5) induced an increase in the total footprint the first year
229 ($+0.2$ % and $+1.4$ % for ST and LHS laboratories, respectively) and a decrease from the
230 second year (-0.4 % and -1.7 % for ST and LHS laboratories, respectively). Such reduction
231 was of the same order but smaller than that computed at the single laboratory scale.⁴² The
232 magnitude of this decrease is a function of the proportion of disposable plastic consumables
233 in purchases emissions and can reach up to -5.6 ± 4.5 % for a LHS laboratory for which
234 this type of purchases represented ~ 8 % of purchases footprint. At last, efficiency and
235 sufficiency measures resulting in a 2-fold reduction in the purchases of scientific consumables
236 (MS6) resulted in a 5.9 ± 4.7 % and a 9.7 ± 7.8 % decrease in the total footprint of ST and
237 LHS laboratories, respectively. These six mitigation strategies are additive and may result
238 in a total 2.7 % decrease for HSS laboratories, 17.5 % decrease for ST laboratories in the
239 case of a pooling by scientific domain and 18.5% decrease for LHS laboratories in the case
240 of a pooling at the regional scale.

241 While the mitigation strategies dealing with catering or furniture may be implemented
242 without a systemic modification of research practices, it is different for the four other strate-
243 gies. Increasing the service life of scientific equipments would benefit from the development

244 of their ecodesign, which could be promoted through the use of environmental criteria in
245 calls for tender. It would also benefit from grant criteria including specifically the repair and
246 maintenance of scientific equipment instead of favoring the acquisition of new one. The pool-
247 ing of scientific equipment is in agreement with the development of research infrastructures
248 at national and international scales.^{43–45} This effort must be continued while paying atten-
249 tion to the well-being of workers. Moreover, switching from single-use plastic consumables
250 to glassware may increase working time, which may reduce productivity. It is also the case
251 of the mitigation strategies based on efficiency and sufficiency. Promoting these strategies
252 would benefit from a switch in the way scientific knowledge is produced and evaluated such
253 as described by the San Francisco Declaration on Research Assessment.⁴⁶ As it happens with
254 the footprint of households, reducing the footprint of research laboratories may imply pro-
255 found changes in our work habits, which might only be possible if they are accompanied by
256 systemic changes.⁴⁷ A crucial question is the use of the financial resources potentially saved
257 when applying these mitigation strategies, i.e. the rebound effect. Indeed, in this simple
258 analysis the surplus is supposed to be spent in activities with zero emissions. Other possibil-
259 ities need however to be considered: i) allocate the surplus to carbon-negative investments,
260 such as building insulation (negative rebound effect); ii) spend it in lower-carbon activities,
261 such as repair (weak rebound); or iii) purchase higher-emission goods or services, such as
262 flying (detrimental rebound). In particular, the effect on the footprint of a reallocation from
263 goods to salaries is complex and needs further study.²⁷

264 Discussion and conclusion

265 Purchases emissions are almost systematically neglected^{15,18,25} when calculating the carbon
266 footprint of higher education institutions, except in few seminal studies.^{16,17,48} However,
267 these works do not separate research and teaching activities, they only analyze a single
268 institution and use a single set of monetary EFs. The average carbon intensity calculated by

269 Larsen et al. for a Norwegian technical university,¹⁶ 0.39 kg CO₂e/€ 2019, is close to the one
270 calculated here for a French database of more than hundred different laboratories (0.33 ± 0.07
271 kg CO₂e/€ 2019). Interestingly, however, Larsen et al did not find significant differences
272 in the carbon intensities between research domains (Tab. S7), in particular with HSS, in
273 contrast to the current work. We thus hypothesize that the distinction between research and
274 teaching activities is important because the heterogeneity of purchases emissions found in our
275 data suggest that mitigation strategies will need to be adapted to each laboratory. However,
276 the results obtained for HSS laboratories need to be considered with caution because only 10
277 footprints from 8 distinct laboratories were available in the GES 1point5 laboratory emission
278 database.

279 In addition, available data of purchases footprints in universities rely on either non-public
280 EF¹⁶ or general-economy EEIO EF databases such as EXIOBASE,⁴⁹ thus not offering a gen-
281 eral method for research laboratories. Our results indicate that the NACRES-EF database
282 allows to calculate laboratory purchases emissions with a 20% precision, although further
283 work needs to be done to refine emissions associated to laboratory instruments. In addition,
284 previous works do not show the great heterogeneity of emissions among research laboratories,
285 both between different emission sources and within purchases alone. Importantly, our data
286 suggest that laboratory budget is the main driver of purchases emissions, in a similar way
287 as income determines the carbon footprint of households.⁴⁷

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

294 The monetary and aggregated approach that we have followed in this study does not
295 allow evaluating mitigation strategies coming from choices of consumables or instruments

296 with lower carbon footprint than their classical counterparts (supply-based strategies). Such
297 mitigation strategies must be subject to specific estimates based on physical factors and
298 data from suppliers. The difficulty of these mitigation strategies is that they require precise
299 determination of the carbon footprints of one type of product from different manufacturers
300 (or of different models of the same supplier). Few data exist for convenience goods that
301 are part of lab purchases such as computers or printer toners. But for most laboratory
302 equipment an additional difficulty is that they are made up of components manufactured in
303 very small series, and LCA databases contain only data on mass-produced products that have
304 high production costs relative to overhead. In consequence, precise process-based carbon
305 footprints are so far inexistent for laboratory equipments or specific consumables, limiting
306 the possibility to evaluate mitigation strategies based on supplier specific processes for labs.
307 Concerning the monetary factor approach, it should be noted that on the long term, general
308 decarbonation of industry worldwide should reflect on decrease of EF monetary ratios.

309 **Methods**

310 **Classification of goods and approach**

311 Services and goods purchased in a laboratory are classified according to the French NACRES
312 nomenclature, used in the accountability of the majority of research institutions in France.⁵⁰
313 Each type of good or service is identified by a code composed of two letters and two numbers.
314 The first letter provides the general category of the purchase, the second letter designs the
315 domain, the first number the sub-domain and the last number the type. There are 1431
316 defined types split into 24 large categories (Tab. S1). In this work, each NACRES code is
317 given an EF covering GHG emissions associated to all stages of its production (cradle-to-gate
318 perimeter). Each NACRES code is given an EF using the *macro* method (see below), and
319 certain types of goods were also attributed a meso or a micro EF (see below), that were used
320 to construct a final hybrid database. This final database contained 1281 macro, 108 meso

321 and 43 micro EFs (Tab. S1). Complete methodology is described in the SI file.

322 **The macro approach**

323 To associate EFs with each NACRES code while having an uncertainty estimate, we used
324 three different EEIO databases of monetary emission factors: the French *Ratios Monétaires*
325 database published by the *Agence De l'Environnement et de la Maîtrise de l'Energie* (ADEME) in
326 2016; the U.S. CEDA³¹ database provided by Vitalmetrics (version 4.8 released in 2014);
327 and the U.S. USEEIO^{32,33} compiled by the US Environmental protection agency (EPA, pub-
328 lished in 2018). Both American databases contain approximately the same 430 categories,
329 while the French ADEME database provides monetary factors for only 38 categories.³⁴ As
330 the NACRES types cannot always be associated to a single category of the EEIO databases,
331 we associated up to 2 ADEME EFs and up to 6 CEDA/USEEIO EFs to each NACRES
332 category (Tab. S1). We proceeded heuristically by attempting to assign all the EEIO cate-
333 gories of commodities that have similarities (in terms of composition and/or manufacturing
334 process) with the products comprised in each NACRES type. To provide a single EF for
335 each NACRES we averaged the allocated EFs, first within each database, and then between
336 databases. For each EF we calculated uncertainties using two methods. First, attribution
337 uncertainties were computed as the standard deviation of the averaging within databases
338 and across databases. Second, a uniform relative uncertainty of 80% was attributed to all
339 EF. For calculating the footprint of a single laboratory we recommend to use the 80% un-
340 certainty. However, for the results displayed in this work, EF uncertainties did not play any
341 role.

342 **The meso approach**

343 To consolidate macro NACRES-FE database, we used a supplier-based approach, using GHG
344 emissions and financial data of companies whose main segments of activity are to manufac-
345 ture products of provide services to the research, analytical and health markets. We gathered

346 emission data from the Carbon Disclosure Project (CDP)³⁶ or from internal reports, and
347 financial data from the annual reports of companies. A limitation of this approach is that, in
348 November 2022, reasonably complete and reliable GHG emissions (including upstream scope
349 3) were available only for few large companies, listed in Tabs. S4 and S2. The emission cate-
350 gories used encompass all upstream activities involved in the production of goods or services,
351 similarly to the cradle-to-gate perimeter of EEIO databases, but also downstream transporta-
352 tion as most shipment costs are included in prices for laboratory products. The meso mon-
353 etary EFs are then computed as $EF_{meso} = (\text{scope 1+2+3 upstream emissions})/(\text{revenue})$.

354 **The micro approach**

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

364 **Data collection and treatment**

365 All data used in this study have been collected with the GES 1point5 web application.^{37,38} For
366 this purpose, a new module has been developed and implemented in the existing application.
367 Volunteer French research laboratories submitted their purchase data through GES 1point5
368 as a csv file with NACRES codes and the associated tax-free purchase price. Since heating,
369 electricity, commuting, professional travels and computers were already included in GES
370 1point5 as dedicated modules, each NACRES code has been allocated a tag called 'Module'

371 that can take five different values: PURCHASE, ENERGY, VEHICLES, TRAVEL and
372 COMPUTER. The monetary approach described here is only used to calculate the emissions
373 of the NACRES types labeled PURCHASE. In this work, purchases emissions are the sum of
374 emissions calculated via the purchases module (via monetary EFs) and the computer devices
375 module (via physical EFs) of GES 1point5. However, emissions related to the devices module
376 were negligible compared to those of the purchases module. Emissions related to the other
377 sources are computed differently by the dedicated modules of GES 1point5 with EFs based
378 on physical flows as described by 37.

379 Data analysis was performed using custom Python routines. The purchases are clas-
380 sified in 7 aggregated categories in order to facilitate the interpretation of the emissions
381 and the identification of action strategies. These categories are *lab.life* (Food, landscaping,
382 leisure, building), *consumables* (Raw materials, chemicals/biologicals and living organisms),
383 *lab.equipment* (Laboratory equipment and instruments), *transport* (professional travel, in-
384 cluding lodging but excluding transport), *info* (computers and audio-video equipment), *ser-*
385 *vices* and *maintenance*. Note that the *info* category only includes the NACRES types that
386 are not accounted for in the COMPUTER module of GES1p5 (see the SI for more informa-
387 tion). A third tag called ‘Poste’ indicates for each type the emission category as described
388 in the standard GHG protocol.²³

389 **Mitigation strategies**

390 Six mitigation strategies (MS) were calculated.

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

395 MS2 assumes a pooling of 50% of laboratory equipments. For the pooling by discipline,
396 the total footprint and the footprint of “equipments” and of “repair and maintenance” were

397 summed by discipline, while for the pooling at the regional scale, the total footprint and the
398 footprint of “equipments” and of “repair and maintenance” were summed by administrative
399 region if at least 9 GHG assessments were available (four regions). The footprint of equip-
400 ments was divided by 2 and the footprint of repair and maintenance was multiplied by 2.
401 The results at the regional scale are the average of four regions.

402 MS3 assumes an 80% decrease in the use of disposable plastic consumables (NACRES
403 codes NB02, NB03, NB04, NB11, NB12, NB13, NB14, NB15, NB16 and NB17). It implies
404 an 80% increase in the use of consumables for washing machines (NACRES code NB34). The
405 first year, it also implies an increase in the purchases of glassware (NACRES code NB43;
406 $EF = 0.23 \pm 0.1 \text{ kg CO}_2\text{e}/\text{€}$) for an amount equivalent of twice the amount of disposable
407 plastic consumables. From the second year, a 5% breakage was assumed. The total footprint
408 and the footprint of disposable plastic consumables and of consumables for washing machine
409 were summed by discipline.

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

413 MS5 assumes a change in diet with an increase in the proportion of vegetarian menu.
414 The total footprint and the footprint of catering services (NACRES codes AA63, AA64)
415 were summed by discipline. According to ADEME, the mean footprint of a traditional meal
416 in France is 2.04 kg CO₂e and the mean footprint of a vegetarian meal is 0.5 kg CO₂e.
417 Assuming a 75 % conversion to vegetarianism, the footprint of catering services was divided
418 by 3.

419 MS6 assumes a 50% decrease in consumables. Two classes of consumables were con-
420 sidered. The first one was laboratory consumables and corresponded to the category “con-
421 sumables”. The second one was consumables for scientific equipments and was included
422 in the category “laboratory instruments”. The footprint of this class of consumables was
423 determined by removing the footprint of equipments to the footprint of the category “labo-

424 ratory instruments”. The total footprint and the footprint of consumables were summed by
425 discipline. The footprint of consumables was divided by 2.

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