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From hemp grown on carbon-vulnerable lands to long-lasting bio-based products: Uncovering trade-offs between overall environmental impacts, sequestration in soil, and dynamic influences on global temperature

Zhou Shen, Ligia Tiruta-Barna, Lorie Hamelin

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1 From hemp grown on carbon-vulnerable lands to long-lasting
2 bio-based products: Uncovering trade-offs between overall
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4 influences on global temperature

5

6 Zhou Shen*, Ligia Tiruta-Barna, Lorie Hamelin

7 TBI, Université de Toulouse, CNRS, INRAE, INSA, Toulouse, France

8 * corresponding author

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24 **Abstract**

25 In this study, the potential of carbon storage in soil combined with mitigation via bio-based
26 products is investigated for the case of 100 years of hemp cultivation on carbon-vulnerable land
27 (CV-lands) in France. The originality of this study lies in the coupling of soil organic carbon
28 (SOC) simulations (over 100 years of hemp cultivation) with consequential life cycle
29 assessment (LCA) to investigate the mitigation potential of different environmental impacts,
30 and the coupling with dynamic LCA to investigate the long-term effects on global warming.
31 When hemp stems (straw) are left on the ground, SOC increases of 25.8 t ha^{-1} are observed
32 over 100 years. However, the greenhouse gas (GHG) emissions that result from diverting the
33 initial land use to hemp cultivation cannot be compensated for and, therefore, this scenario
34 cannot mitigate global warming or most other impacts. Two long-lasting product scenarios were
35 studied: insulation boards in buildings and car panels, both involving the production of hemp
36 concrete as co-product. Our study shows that, even though no additional long-term carbon
37 sequestration in soil could be achieved, both scenarios ensured a long-term climate benefit well
38 beyond 2100, mostly because of carbon sequestered in the hemp-based products but also as a
39 result of avoided fossil-based products. Uncertainty analyses reveal that the yield is the most
40 influential parameter, inducing significant uncertainties in all scenarios and most impact
41 categories. According to the overall results obtained, the car panel scenario is the most
42 promising pathway with the lowest environmental impacts and the highest potential for long-
43 term global warming mitigation; this is in part due to the reduction of fuel consumption during
44 the use phase.

45

46 **Keywords:** soil organic carbon, consequential life cycle assessment, dynamic life cycle
47 assessment, climate change mitigation, bio-based products, negative emissions

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49 **Highlights**

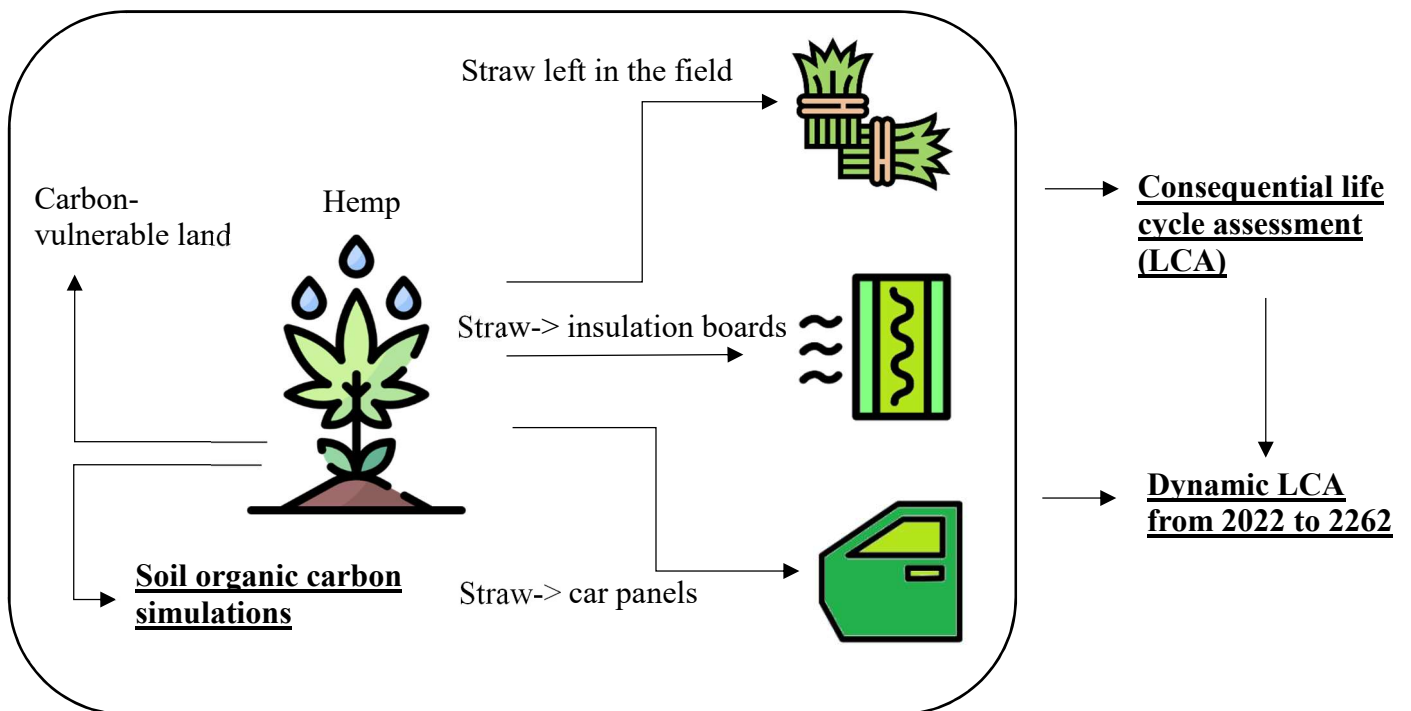
- 50 • Using hemp straw in materials is climatically preferable to leaving straw in fields
- 51 • Leaving straw on the ground maximizes the soil organic carbon stock
- 52 • Leaving straw on the ground reduces the climate mitigation
- 53 • Negative emissions are temporary and depend on carbon storage in products
- 54 • Avoided emissions from anthropogenic processes determine the scenario ranks

55

56 **Graphical Abstract**

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58



59 **1 Introduction**

60 In response to global warming, many governments, including France, signed the Paris
61 Agreement calling for limiting global warming to well below 2 °C above pre-industrial levels
62 by 2100 and further committing to achieving carbon neutrality prior to 2050 (Boudet et al.,
63 2021; UNFCCC, 2015). These climate targets imply increasing and safeguarding carbon sinks
64 such as soil and plants. This requirement inspired the concept of simultaneous carbon storage
65 in arable land and anthropogenic products (CSAAP), a strategy to use plants that can store
66 additional carbon in the soil as soil organic carbon (SOC) during the growth phase and in the
67 technosphere as bio-based products obtained from the harvestable biomass (Shen et al., 2022).
68 Accordingly, CSAAP implies simultaneously inducing negative emissions and emission
69 mitigation. To avoid risks such as decreasing food security, the cultivation of such plants
70 (referred to as biopumps) needs to be conducted on land that would not otherwise supply
71 products to the market and where the SOC can be increased. Such land is referred to here as
72 carbon-vulnerable (CV) land. CV land is marginal land that does not compete with crops or
73 with other existing activities and has a low SOC stock, defined as lower than 50 t ha⁻¹ in (Shen
74 et al., 2022). The selection of this land type in the French landscape has been explained in a
75 previous study (Shen et al., 2022) that identified up to 2,400,000 ha of CV land that could
76 potentially be adapted to conduct CSAAP in France using eight woody species and eight
77 herbaceous plants. As a promising species, hemp (*Cannabis sativa L.*) is proposed in this study
78 to evaluate the application of CSAAP in France. France is the leading hemp cultivator in Europe,
79 accounting for 40% of European production, corresponding to 18,000 ha of arable land (Carus
80 and Sarmiento, 2017; Raymunt, 2020). However, hemp could also be grown on CV land.

81 Unlike most fiber crops (e.g., flax), additional carbon storage in the SOC pool has been
82 observed during hemp cultivation. Previous studies have reported that 100–300 kg CO₂ ha⁻¹

83 year⁻¹ is potentially stored in soil cultivated with hemp in France (Boutin et al., 2006). Similarly,
84 annual SOC increases of 0.14–0.15 g kg⁻¹ have been reported in China (Li et al., 2012).

85 Hemp can be used in a variety of materials and products, with construction materials and
86 the automotive industry being two sectors with the greatest growth potential (Hemp benchmarks,
87 2021). Using hemp instead of conventional materials could not only supply the same functions
88 but also produce additional benefits such as reducing the weight of composites. For example,
89 Audi has implemented the use of hemp fiber to construct side panels in one of their models (A3)
90 instead of acrylonitrile butadiene styrene plastic, which reduces the weight of the vehicles and
91 consequently their fuel consumption (Akampumuza et al., 2017). If 50% of glass fiber is
92 replaced by natural fiber in the North American automobile market, then 3.07 million tons of
93 CO₂ and 1.19 million m³ of crude oil could be saved as a result of the reduced car weight
94 (Pervaiz and Sain, 2003).

95 However, the relevance of the full-scale cultivation and use of hemp needs to be evaluated
96 to demonstrate its mitigation potential for climate change and to anticipate potential adverse
97 effects. Previous studies have used the life cycle assessment (LCA) method to assess the
98 environmental impacts of hemp-based products. These studies used different allocation
99 methods for the produced co-products, allocating the impacts by mass or economic value (Deng,
100 2014; Sinka et al., 2018) or excluding important co-products such as shives (Andersson and
101 Björhagen, 2018). Moreover, very few LCAs of hemp bio-products have considered a detailed
102 assessment of the emissions occurring during the cultivation stage, including those associated
103 with SOC changes; instead, such studies have tended to focus on the manufacturing stage (e.g.,
104 Senga Kiessé et al., 2017).

105 To the best of the authors' knowledge, no previous study has evaluated the climate
106 mitigation potential and overall environmental impacts of a hemp-based CSAAP strategy for a
107 country. To bridge this gap, the goal of our study is four-fold: (i) to evaluate the long-term

108 carbon sequestration performance of hemp grown on French CV land; (ii) to assess the overall
109 environmental consequences of converting CV land for the cultivation of hemp and
110 subsequently transforming the harvested hemp into long-lasting bio-based products, thereby
111 replacing petrochemical counterparts; (iii) to uncover the trade-offs of this hemp-to-
112 bioeconomy product concept between carbon sequestration in soil and climate change
113 mitigation, as well as those between the different environmental impacts; and (iv) to assess the
114 effect of this CSAAP system on the global temperature change over time.

115 Accordingly, three scenarios are used to investigate hemp cultivation on CV land and its
116 use in two different bio-based products with different lifetimes. While all three scenarios
117 involve the cultivation of hemp and the harvest of hemp seeds with the subsequent production
118 of hempseed oil, they differ with respect to their use of the hemp straw (i.e., the hemp stem).
119 These three scenarios are (i) incorporating the hemp straw into the soil, (ii) harvesting the hemp
120 straw to produce thermal insulation for buildings, and (iii) harvesting the hemp straw to produce
121 car panels.

122

123 **2 Methods**

124 **2.1 Overview of the step-wise approach**

125 To determine the environmental performance of cultivating hemp on CV land, the SOC
126 change in the soil was first simulated based on a state-of-the-art SOC model. The result was fed
127 into consequential life cycle inventories, together with inputs and outputs from the other
128 involved processes (Fig. 1); this was then translated, via a life cycle impact assessment (Fazio
129 et al., 2018), into the net environmental impacts for all three scenarios. The effect of the
130 temporality of the carbon emission and capture processes over the entire life cycle was
131 evaluated for the climate change impact using a dynamic LCA approach. As required by the

132 International Organization for Standardization (ISO) standards for LCA (ISO, 2006a, 2006b),
133 sensitivity and uncertainty analyses were conducted to explore the robustness of the results.

134

135 **2.2 Assessing SOC changes associated with converting CV land for hemp cultivation**

136 French CV land was identified (Shen et al., 2022) as areas currently under the following
137 landcovers (reported as the percentage of the total CV-land area): (i) rapeseed cultivation (20%),
138 (ii) intensive grasslands (53%), (iii) natural grasslands (20%), and (iv) woody moorlands (7%).
139 This represents the reference management of the CV land prior to its conversion to hemp. Here,
140 a few simplifications were made to ensure tractability. First, heather (*Calluna vulgaris*) was
141 selected as a representative biomass species for both the natural grasslands and the woody
142 moorlands based on the definitions provided in the literature (Inglada et al., 2017). Similarly,
143 ryegrass (*Lolium perenne L.*) and rapeseed (*Brassica napus L.*) were chosen as representative
144 species of intensive grassland and rapeseed cultivation, respectively (Kirwan et al., 2007).
145 Accordingly, a representative hectare of the “initial French CV-land management” is here
146 defined as 20% rapeseed cultivation, 53% perennial ryegrass cultivation, and 27% heather
147 natural growth.

148 The 100-year SOC evolution associated with these three CV-land management types, and
149 that with hemp cultivation (with and without straw harvest), were quantified using the AMG
150 soil simulation model (detailed in Clivot et al., 2019) and calibrated to estimate the topsoil (<30
151 cm) SOC changes under hemp cultivation conditions in France. Inputs to the AMG model
152 include meteorological data (mean yearly temperature, precipitation, and evapotranspiration),
153 soil characteristics (clay and rock percentage, C/N ratio, and topsoil depth), agricultural
154 management (tillage type and depth and amount of water supplied via irrigation), and carbon
155 input from both biomass (above and below ground) and other eventual sources (e.g., manure
156 and compost). The model runs year by year, here, from 2022 to 2122. For simplicity, the

157 agricultural management parameters were considered to not vary over the studied 100-year
158 period. Similarly, the same starting point in terms of the initial SOC stock (42.35 t ha^{-1}) and
159 other soil characteristics (Table A.S1) were considered for all types of CV land. These figures
160 represent the weighted average for the four types of CV land and were derived from data
161 extracted from the Harmonized World Soil Database (v1.2; FAO, 2021) (Nachtergaele et al.,
162 2012). Because there is no comparable information for the C/N ratio, three C/N ratios were
163 tested for the hemp scenarios (both with and without straw harvest), namely, 11, 17, and 22,
164 based on available data for France (Clivot et al., 2019; Conen et al., 2008; Delmas et al., 2015).
165 For the initial CV-land management, however, only a default C/N value of 17 was considered.
166 All soil characteristics (except SOC) were assumed to remain constant over the 100-year period.
167 Future yearly meteorological data averaged over France were retrieved from the gridded climate
168 data information (SICLIMA) maintained by the French National Research Institute for
169 Agriculture, Food and Environment (DRIAS CERFACS, IPSL, last updated May 2013) for the
170 Representative Concentration Pathway (RCP) 4.5 climate trajectory (Chen et al., 2021),
171 downscaled by the CNRM-CERFACS-CM5/CNRM-ALADIN63 model. These downscaled
172 projections are not available beyond 2100. Therefore, for the period from 2101 to 2122, average
173 values from the final available decade (e.g., from 2091 to 2100) were used.

174 The above- and below-ground carbon inputs from hemp were calculated (Agostini et al.,
175 2021) considering a harvest index of 0.9, a shoot/root ratio of 3.78 (Clivot et al., 2019), and a
176 yield of 9.19 t ha^{-1} dry matter (DM). This value of the yield reflects the average of a compilation
177 of yield data from hemp grown in France and neighboring countries (as further detailed in Table
178 A.S2); therefore, it could be smaller under the actual conditions of a given CV-land area.
179 Accordingly, the yield is included in the sensitivity analysis. Note that the AMG model
180 considers, for hemp straw, a technically harvestable rate of 100%. Yields of 8 and 2.2 t DM
181 $\text{ha}^{-1} \text{ year}^{-1}$ were considered for ryegrass and rapeseed, respectively, with shoot/root ratios of 1

182 and 3.26, respectively and harvest indices of 0.83 and 0.25, respectively (Table A.S15). Unlike
183 hemp, ryegrass, and rapeseed, heather is not included in the AMG model, which was calibrated
184 for cultivated plants. Therefore, SOC changes consisting of a 10% SOC increase in the topsoil
185 after 100 years were considered (Pehme et al., 2017) to represent a system in which “heather
186 was left as heather.” This is a conservative assumption for a modeled system in which hemp is
187 cultivated instead of natural heather. The 100-year SOC difference between hemp cultivation
188 and each initial CV-land management type could then be calculated.

189 **2.3 Assessing the environmental consequences of selected CSAAP scenarios: Static LCA**

190 The environmental consequences of the studied CSAAP scenarios were assessed using
191 LCA, a standardized (ISO, 2006a, 2006b) and leading environmental assessment methodology,
192 recognized as a suitable tool to anticipate the consequences of long-term investment decisions
193 (i.e., change-oriented studies; Brandao et al., 2017; Sala et al., 2021; Weidema et al., 2013).
194 Consequential assessment implies that multi-functionality is handled with system expansion
195 and that marginal suppliers are considered (i.e. those reacting to demand changes). Moreover,
196 full elasticity of supply was considered for product substitutions (Weidema et al., 2013)
197 involving 1:1 substitution ratios. This implies that short-term effects induced by price changes
198 are disregarded.

199 All input and output flows were related to the functional unit (FU), which was the annual
200 management of 1 ha of representative CV land. The annualization technique was used for all
201 the processes involving releases that occurred over several years, i.e. such emissions were
202 linearly distributed over the corresponding period to generate an annual emission. Because of
203 this one-year temporal scope, we refer to this type of assessment as “static LCA.” Unless
204 otherwise specified, the inventory data were based on a compilation of data retrieved from a
205 comprehensive literature review; either the averages or the median of these compilations were
206 used, as further detailed in Supplement information (SI) A (Tables A.S3–S20). The induced

207 SOC changes were retrieved from the AMG simulations (Section 2.2). The amounts of all end-
208 products generated in the three scenarios were linked to the FU via the hemp yield,, with 0.83
209 t DM seeds ha⁻¹ and 8.37 t DM straw ha⁻¹ (Ventura and Kiess, 2015), considering annual
210 fertilization rates of 107 kg N ha⁻¹, 51 kg P ha⁻¹, and 90 kg K ha⁻¹ (Table A.S3). For all
211 scenarios, hempseed meal was produced and used as a source of carbohydrates, proteins, and
212 lipids, which accordingly replaced the production of marginal proteins, carbohydrates, and
213 lipids(soybean meal, maize, and palm oil, respectively (Tonini et al., 2016).

214 Three scenarios of hemp use corresponding to different anthropogenic bio-based products
215 were considered and assessed.

216 1) In the SL (straw left on ground) scenario, only the seeds are harvested, with 50 kg (fresh
217 weight) of the harvested seeds being re-sown in the next rotation (Ventura and Kiess, 2015)
218 and the remaining 925 kg of seeds being used to extract 296 kg of hemp oil, replacing the
219 production of the same amount of palm oil. The seed meal after oil extraction is used for
220 animal feed, thereby replacing marginal feed ingredients. The corresponding substitution in
221 terms of avoided soybean meal, maize, and palm oil was calculated based on the
222 methodology presented in Tonini et al. (2016). The hemp oil is assumed to be consumed in
223 the year following its production, and all carbon in the oil is assumed, for tractability, to be
224 emitted as CO₂. The hemp straw is left to decay on the ground.

225 2) In the IB (insulation board) scenario, both the seeds and the straw are harvested. The
226 harvested seeds go through the same pathway as in the SL scenario. The harvested straw is
227 then processed for fiber separation. In addition to fiber (circa 30% of the straw DM), shives
228 (65%) are obtained as a by-product with lower economic value and the remaining 5% is lost
229 as dust (Norton et al., 2009). Shives can be further mixed with lime and water to produce
230 hemp concrete, which is considered in this scenario (with proportions of 17.8% shives, 32.9%
231 lime, and 49.3% water for 1 m³ of hemp concrete; Table A.S9). Because of the lower strength

232 of hemp concrete compared with traditional concrete, this product is assumed to replace
233 gypsum board based on their similar densities (Jiménez Rivero et al., 2016). During its use,
234 hemp concrete absorbs CO₂ via a carbonation mechanism. Here, based on Pretot et al. (2014),
235 we assumed that 77 kg CO₂ is absorbed per m³ over the entire lifespan of the concrete. The
236 separated hemp fibers are mixed with additives to become fire retardant and are subjected to
237 thermocompression, resulting in the production of insulation boards; these processes were
238 modeled based on data from Andersson and Björhagen (2018) and Stapulionienė et al. (2016)
239 (Table A.S10). The thermal conductivity properties considered for the produced boards are
240 detailed in the SI A, in Section 2.8. A lifetime of 40 years was considered for the produced
241 boards (Andersson and Björhagen, 2018). The produced hemp insulation boards can reduce
242 the production of conventional insulation materials. In generic, conventional products that
243 provide similar function but are less competitive in the market (in the marginal place), were
244 selected to be avoided by hemp based products (Brandao et al., 2017). For example, herein
245 the production of hemp insulation boards would lead to less production of insulation boards
246 by mineral wool (Uihlein et al., 2008). At the end of life, the boards are assumed to be
247 landfilled in installations without CH₄ recovery (Norton, 2008). This is a conservative
248 assumption. We assumed that all the biogenic carbon would eventually degrade, with 19.98%
249 degrading in the first 100 years (87% as CO₂ and 13% as CH₄) according to the
250 Intergovernmental Panel on Climate Change (IPCC, 2019). On this basis, for the static LCA,
251 we assumed that 2.6% of the biogenic carbon contained in the board would end up being
252 emitted as CH₄, while the rest would be emitted as CO₂.

253 3) In the CP (car panel) scenario, both the seeds and the straw are harvested and processed
254 in the same manner as in the IB scenario. However, as the main product of this scenario, the
255 separated hemp fibers are used to produce lightweight car panel structures with a lifetime of
256 12 years (La Rosa et al., 2013; Wötzel et al., 1999). During the use stage, the new lighter

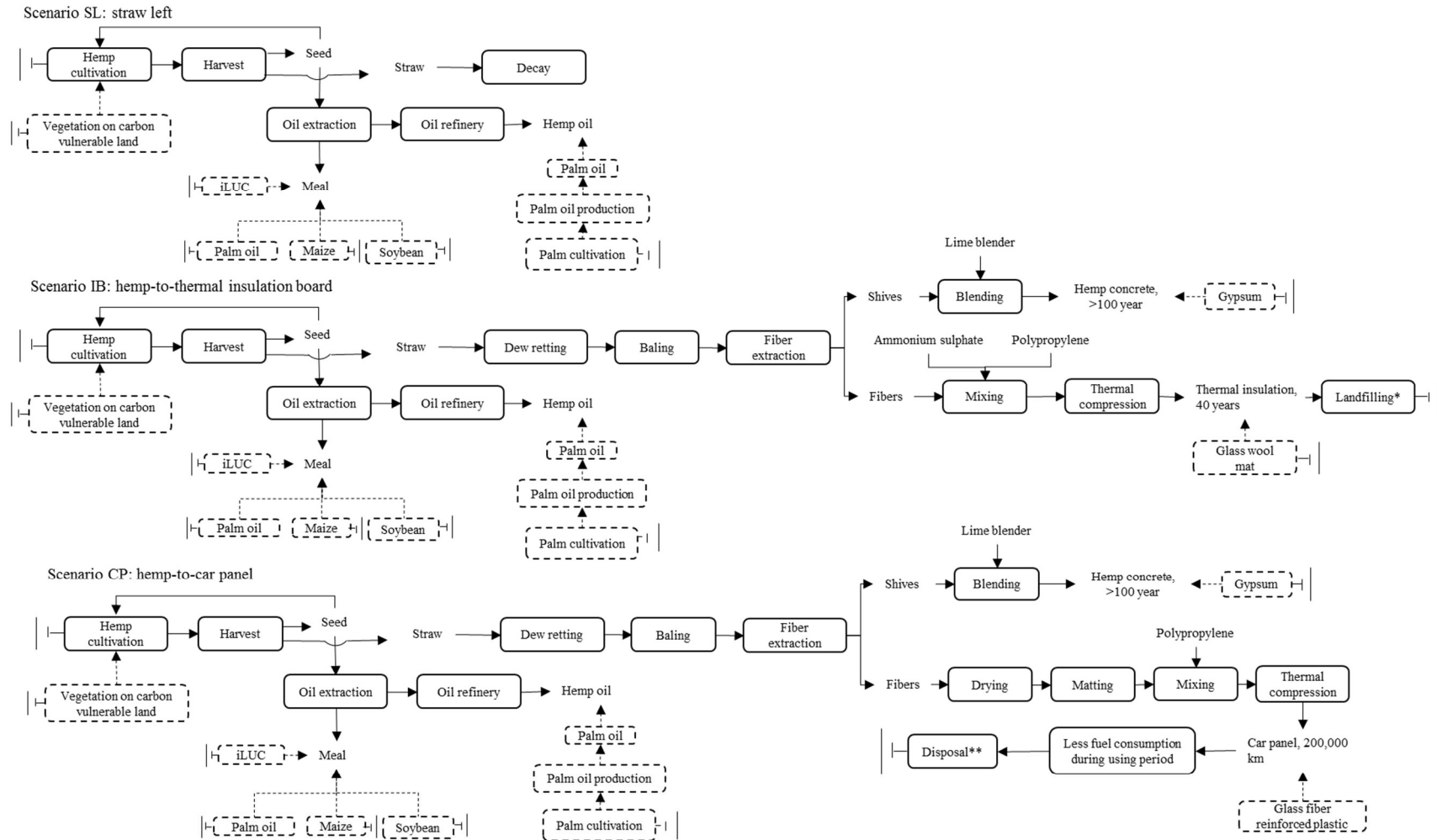
257 material allows vehicles to have a lower fuel consumption compared with vehicles using
258 conventional glass fiber panels (Deng, 2014). Here, reduction of 2.35 L of gasoline per kg
259 car panel was assumed over the lifetime of the panel (Section A.2.11). Based on Gueudet
260 (2016), it was assumed that 30% of the hemp car panels would be incinerated with power
261 recovery at the end of life, while 70% would be landfilled (no CH₄ recovery). Landfilling
262 emissions were calculated in the same manner as in the IB scenario.

263 The conventional CV-land management was modeled distinctly for the three chosen types
264 of landcover. It was assumed that the ryegrass would have been used as cattle silage. This
265 implies that this nutritional service would no longer be supplied and would need to be provided
266 from elsewhere, thereby inducing an additional demand for animal feed ingredients. As for
267 hempseed meal, this was modeled using the method of Tonini et al., (2016). It was similarly
268 considered that the rapeseed would have been used to produce rapeseed oil and meal. Here,
269 palm oil is assumed to be the marginal vegetable oil reacting to the rapeseed oil no longer being
270 supplied (Schmidt and Weidema, 2008); this was modeled using the consequential Ecoinvent
271 database (Table A.S17; dataset market for palm oil, which already includes interactions with
272 meal). The changed management from both rapeseed and ryegrass to hemp therefore involves
273 land use changes, and the emission flows related to these were modeled according to the method
274 described in Tonini et al., (2016) (Table A.S20). Conversely, it is assumed that the heather from
275 the natural grasslands and woody moorlands would have been left unharvested and simply
276 decayed on site (Tables A.S18 and A.S19).

277 The system boundaries considered for the three scenarios are summarized in Fig. 1, and the
278 corresponding inventory tables are available in the SI. A (Sections 2.2–2.14). Background data
279 (e.g., electricity, fertilizer production, and machines used in manufacturing) were primarily
280 extracted from the Ecoinvent v3.5 consequential life cycle inventory database. Foreground data
281 were estimated based on published literature and simulations, as described above.

282 On the basis of a recent European Commission Recommendation (EC, 2021), the
283 Environmental Footprint v2.0 life cycle impact assessment method (Fazio et al., 2018), which
284 assesses 16 impact categories, was used to evaluate the environmental impacts of the scenarios
285 (Table A.S22). The LCA was implemented using the SimaPro software, version 9.1.1.
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305 **Fig. 1.** Process flow diagram and system boundaries considered for the three assessed scenarios. The boxes indicate processes, with the solid lines
 306 indicating induced processes and the dotted lines indicating avoided processes. *Landfilling without CH₄ recovery. **30% of the car panel material
 307 is disposed of via incineration with power recovery, while the rest is disposed of via landfilling without CH₄ recovery.

308 **2.4 Dynamic inventory for greenhouse gas flows and assessing related temperature** 309 **changes**

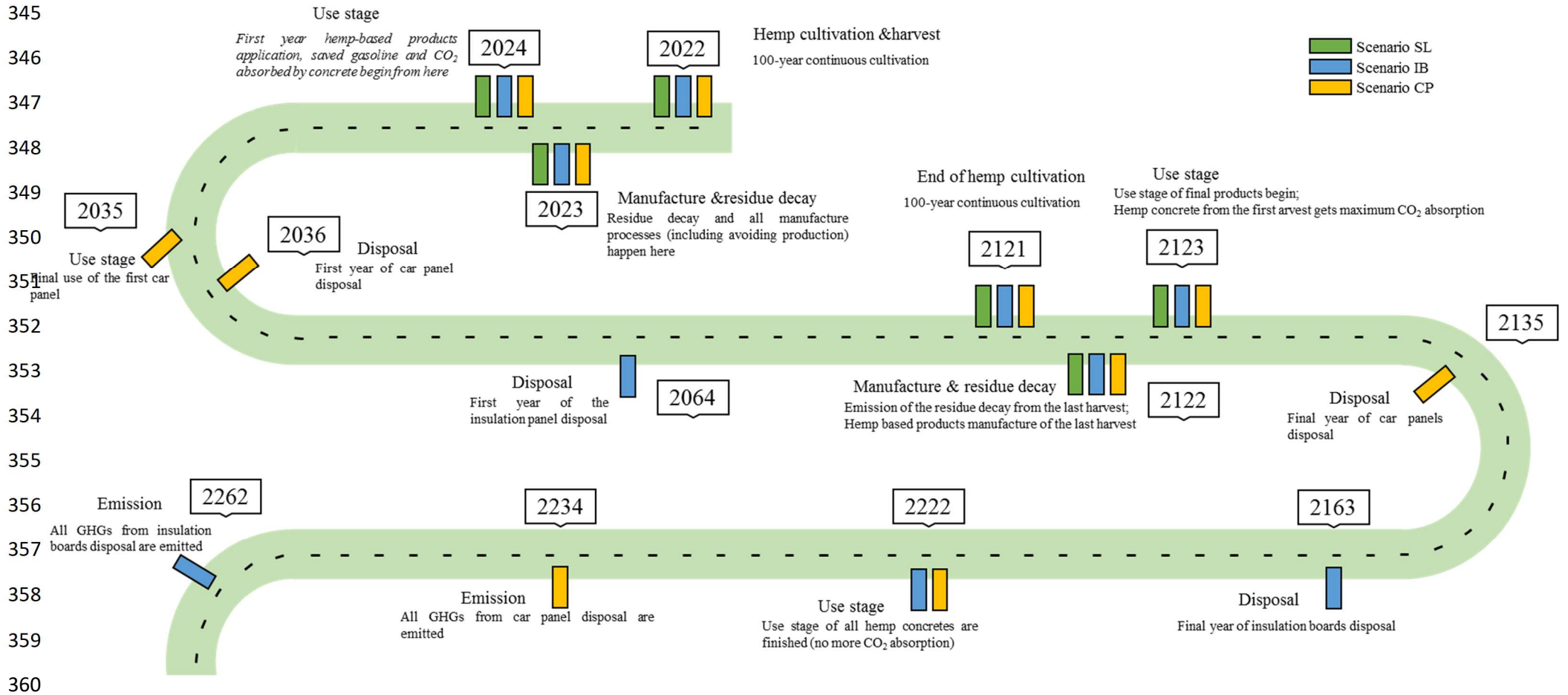
310 One manner in which the analyzed systems were characterized was via the distinct
311 temporalities of the processes they involve; these temporalities have significant effects on the
312 climate change impacts of the systems. In dynamic LCA, the extent of global warming is
313 described via the global mean temperature change (GMTC), which is based on the impulse
314 response function approach recommended by the IPCC (Stocker et al., 2013). This indicator is
315 calculated as a function of time and depends on the nature of the greenhouse gas (GHG) and
316 the emission dynamics. Here, GMTC is calculated using the CCI-tool (Tiruta-Barna, 2021;
317 Shimako et al., 2016), which is available online (Tiruta-Barna, 2021).

318 The time scale of the FU (i.e. 1 ha of land) was set to 100 years of continuous hemp
319 cultivation starting in 2022. The time scale of the inventory is much longer as a result of the
320 lifetimes of the products (e.g., 40 years for thermal insulation) and because of the duration of
321 the end-of-life processes (e.g., emissions from landfilling). Notably, for bio-based products,
322 natural degradation can take several decades (IPCC, 2019). For the temporal inventory and for
323 the GMTC calculation, a time step of 1 year was adopted; this time step was considered to be
324 sufficient (Shimako et al., 2018).

325 Because hemp is an annual crop, cultivation (including plant carbon uptake and
326 agricultural processes) and harvesting take place during the same year. The SOC change
327 simulated in Section 2.2 was incorporated into the corresponding year annually until the end of
328 cultivation. Activities and SOC changes beyond 100 years of cultivation are out of the scope.
329 The manufacturing and above-ground residue fate (part is mineralized and part enters the SOC)
330 was assumed to finish in one year after cultivation (year 2); therefore, the use stage of the
331 product begins in the third year (Fig. 2). The delay between the consecutive manufacturing unit
332 processes was assumed to be negligible. After the lifetime of the product, disposal was

333 considered. If the products are incinerated, GHGs are immediately emitted to the atmosphere.
334 In the case of landfilling, GHGs (mainly CH₄ and CO₂) are gradually released following first-
335 order decay kinetics (IPCC, 2019) (SI. C). The factors adopted in the calculation are global and
336 not country specific because the use of the hemp-based products could occur anywhere. For
337 hemp concrete, landfilling is the most common practice; in this case, there is no decomposition
338 of the material at the end of life, which means no GHG emissions (Pretot et al., 2014). A
339 timeline representing the three scenarios is shown in Fig. 2. The temporal life cycle inventory
340 (LCI) was obtained from the consequential LCI by spreading the processes with their
341 inventories over the timeline (SI. C). The temporal LCI for each scenario was then used for
342 time-dependent GMTC calculations over a time horizon of 241 years for all the GHGs in the
343 Ecoinvent database (Table A.S23).

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361 **Fig. 2.** Timeline considered in the dynamic life cycle assessment (LCA) for the three scenarios. In the SL scenario, in which the straw is left on the
 362 ground, “residues” refer to the entire straw, while in the IB and CP scenarios, in which the hemp fibers are used for insulation boards and car panels,
 363 respectively, “residues” refer to the un-harvestable above-ground portion of the straw only. Here, GHG indicates greenhouse gas.

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365 **2.5 Sensitivity and uncertainty analyses**

366 Sensitivity analyses were performed to test the sensitivity of the result to two modeling
367 hypotheses: (i) the use of fertilizers and (ii) the type of fuel being used for personal cars in the
368 long term. It can be argued that biopumps grown on CV land (with the intention of increasing
369 the SOC and mitigating the overall environmental performance) belong to a “low-input” type
370 of agriculture. Here, this is considered using a zero-fertilization sensitivity analysis. Fertilizers
371 generate GHGs not only via their production but also during the use phase, e.g., extra N₂O
372 emissions occur as a result of the extra available nitrogen via microbial nitrification and
373 denitrification (Hergoualc’h et al., 2019). If fertilization is excluded in hemp cultivation, these
374 GHG emissions can be avoided; however, the yield will also be reduced, leading to less
375 captured CO₂ and a smaller amount of biomass for downstream manufacturing processes. A
376 sensitivity analysis permits an investigation of the relationship between the fertilizers, the yield,
377 and the environment. Here, a yield reduction of 60% compared to the default case (Aubin et al.,
378 2015; Vera et al., 2010) was considered for this zero-fertilization sensitivity analysis.

379 The second sensitivity analysis is based on the announcement by the French government
380 that thermal combustion engine cars will no longer be sold after 2040 and will be replaced by
381 cars using less GHG-intensive energy sources (“Climate Plan,” 2017). Therefore, starting in
382 2040, the saved gasoline consumption in the CP scenario is replaced by saved electricity
383 consumption in both the static and dynamic LCAs.

384 The uncertainty analysis was conducted according to the global sensitivity analysis (GSA)
385 method proposed by Bisinella et al. (2016). GSA unifies the concepts of uncertainty and
386 sensitivity (e.g., for small parameter variations, in the order of 10%). In the first step, the
387 parameters with high contributions to the environmental impacts were selected based on the
388 contribution analysis results from the static LCA (Tables B.S3–S61). Then, a perturbation
389 analysis was performed, in a one-at-a-time fashion, considering how a variation of 10% in each

390 of these parameters affects the normalized results; this approach is further described in the SI.
391 A (Section 5.1). A probability distribution (triangular or normal) was assigned to each
392 parameter, allowing use of the analytical method proposed by Bisinella et al. (2016) to calculate
393 the contribution of each parameter to the overall system uncertainty, impact by impact. The
394 coefficient of variation was used to represent, for each impact, the overall system uncertainty.

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396 **3 Results and discussion**

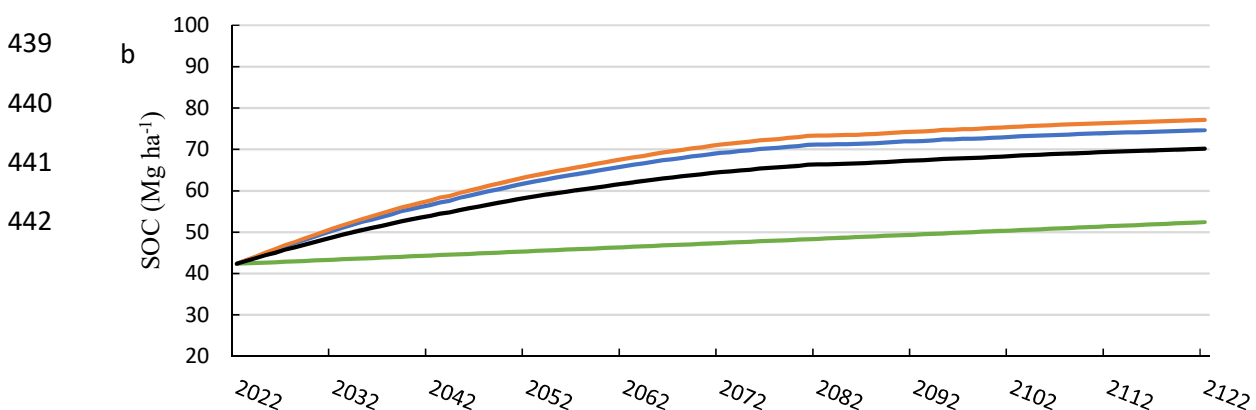
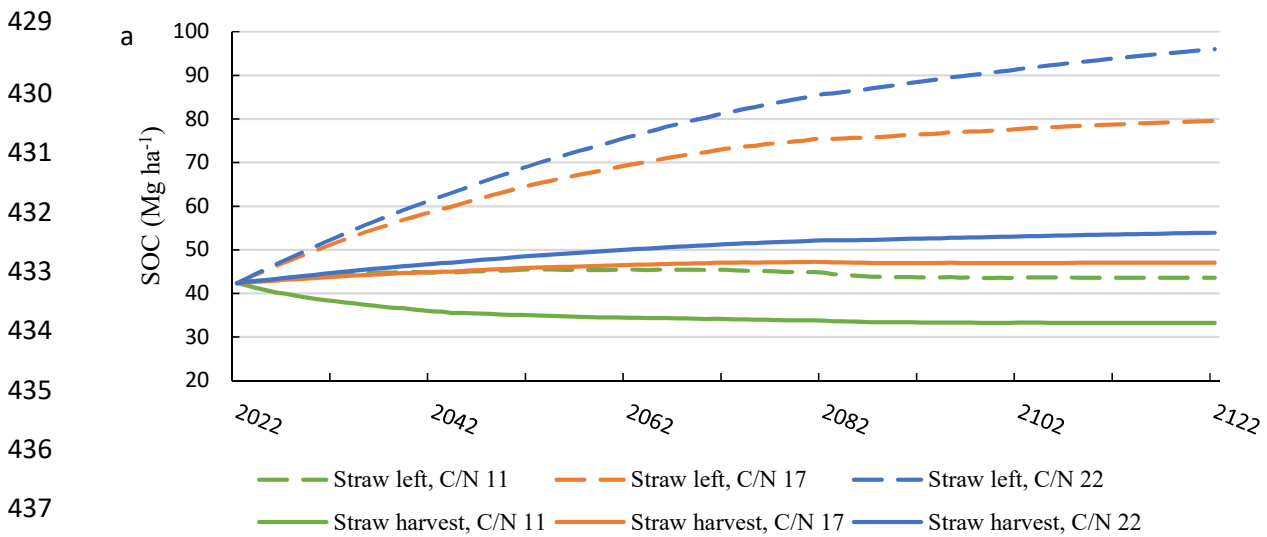
397 **3.1 SOC simulation using the AMG model**

398 Fig. 3a presents the 100-year SOC (<30 cm) simulated for hemp, with and without
399 harvesting straw and considering different soil C/N ratios. This can be contrasted with Fig. 3b,
400 where the SOC evolution related to the conventional CV-land management is presented, both
401 for individual and weight-average French CV-land types. As can be seen in Fig. 3a, in all but
402 one case (straw harvest with a C/N ratio of 11), hemp allows a long-term increase in the SOC
403 stock in comparison with a given initial level of 42.35 Mg C ha⁻¹. This represents increases
404 varying between 1.26 Mg C ha⁻¹ (straw left on the ground with a C/N ratio of 11) and 53.68
405 Mg C ha⁻¹ (straw left on the ground with a C/N ratio of 22). If annualized, this corresponds to
406 0.0126 and 0.537 Mg C ha⁻¹ year⁻¹, which is in agreement with previous studies (e.g., increases
407 of 0.36–0.4 Mg ha⁻¹ year⁻¹ reported by Li et al. (2012), where straw was left unharvested).
408 However, a CSAAP strategy implies harvesting (and using) the hemp straw. Fig. 3a shows that,
409 when hemp is grown on CV land and is fully harvested, a 100-year SOC increase from just 4.68
410 Mg C ha⁻¹ (straw harvested with a C/N ratio of 17) to 11.56 Mg C ha⁻¹ (straw harvested with a
411 C/N ratio of 22) is obtained. This is rather small in comparison with the increase of 27.84 Mg
412 C ha⁻¹ (C/N = 17) observed on average CV land (Fig. 3b). In other words, when considering
413 the SOC evolution that would have otherwise occurred over the 100-year period, the hemp
414 CSAAP strategy is rather uncompetitive on French CV-land, leading to a net SOC change of -

415 27.68 Mg C ha⁻¹ (i.e., no additional sequestration). This would be exacerbated by the greater
 416 proportions of intensive grassland and rapeseed land in the CV-land mix. This is, in part,
 417 explained by the important below-ground carbon input of ryegrass, which is three times higher
 418 than those of hemp (2.77 Mg ha⁻¹ for ryegrass versus 0.89 Mg ha⁻¹ for hemp, Tables A.S2 and
 419 A.S15), and by the very minor share (ca. 25%) of the above-ground biomass harvested in the
 420 rapeseed system.

421 Regardless of whether hemp straw is harvested, the higher C/N ratio leads to higher SOC
 422 increases. This reflects the fact that, when the C/N ratio increases, mineralization decreases (in
 423 part as a result of increased immobilization by soil microbiota), leading to a slower
 424 decomposition of the soil organic matter (Clivot et al., 2019). This result is consistent with
 425 experimental measurements (Clivot et al., 2017). With respect to assessing the sequestration
 426 performance of a CSAAP strategy, the C/N ratio is therefore a sensitive parameter for which
 427 high data quality is important.

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Fig. 3. Evolution of the 100-year soil organic carbon (SOC) stock (a) with different C/N ratios for hemp cultivation on average carbon-vulnerable (CV) land and (b) for the initial vegetation on the CV land with a C/N ratio of 17.

3.2 Environmental performances of the three hemp scenarios

The compared environmental performances of the three scenarios are shown in Fig. 4, with the breakdown per process for four impact categories. The LCA results for all of the other impact categories are available in SI. B, along with the contribution analysis. In Fig. 4, all processes above the abscissa represent the studied contributions to the environmental impact, while those below the abscissa (negative) represent the avoided impacts. The dots indicate the net scenario performance. Fig. 4 indicates that, for all impacts presented in the figure, the IB and CP scenarios allow a net negative overall impact. This means that the benefits associated with implementing these scenarios are greater than those associated with leaving the system as is (i.e., conventional CV-land management and the production of petrochemical products). However, this conclusion does not apply to the SL scenario with respect to the impacts to climate change (net 971.18 kg CO₂-eq ha⁻¹) and freshwater eutrophication (net 1.74 kg P-eq ha⁻¹).

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495 In the SL scenario, the soil in the 1 ha of CV land can store an amount of carbon equivalent
496 to 1.35 t CO₂ (Fig. 3), which is greater than the net climate change result for this scenario.
497 However, this SOC increase results in less carbon transported to downstream processes and
498 higher CO₂ and N₂O emissions during residue decomposition (18.1 t CO₂ and 1.49 kg N₂O in
499 the SL scenario and 4.81 t CO₂ and 0.46 kg N₂O in the IB and CP scenarios). In the IB and CP
500 scenarios, because the straw is harvested, there is more straw carbon ending up in the
501 technosphere than in the soil; therefore, the benefit from the SOC enhancement (−170 kg CO₂-
502 eq) is smaller than that in the SL scenario.

503 Fig. 4 highlights the importance of the avoided petrochemical counterfactuals in the IB
504 (mineral wool insulation boards; in yellow) and CP (glass fiber car panels; light green) scenarios
505 for all impact categories. Avoiding wool-based boards is beneficial to climate change, non-
506 cancer human health effects, and freshwater and marine eutrophication (−13.32 t CO₂-eq,
507 −0.001 CTUh, −5.97 kg P-eq, and −14.17 kg N-eq per FU, respectively, which represents
508 29.12%, 11.84%, 94.9%, and 31.55% of the negative scores, respectively). The avoided car
509 panels are also beneficial to the same impact categories (−31.96 t CO₂-eq, −0.004 CTUh, −5.97
510 kg P-eq, and −23.72 kg-N eq per FU, respectively, which represent 47.75%, 26.25%, 28.16%,
511 and 29.4% of the negative scores, respectively). The high contribution of the avoided products
512 means that the manufacturing of hemp-based materials performs better than the manufacturing
513 of conventional materials, which is in agreement with previous studies (Ardente et al., 2008;
514 Kim et al., 2008; Norton, 2008; Tadele et al., 2020; Zampori et al., 2013). Of course, these
515 benefits exist as long as the substitution of petrochemical counterparts is possible, which seems
516 to be the case for the upcoming 10 years (Grand view research, 2021, 2019). Considering that
517 the time scale of this study is from 2022 to 2122, it is difficult to predict the development of the
518 replaced products over such a long-term period; it is possible that, with the development of new

519 technologies, emissions from producing insulation boards and car panels, whether based on
520 new or conventional materials, could be significantly reduced (Jiménez Rivero et al., 2016;
521 Schwarz et al., 2021).

522 Compared with avoided wool-based boards, the negative climate change score of the
523 avoided car panels is primarily due to the extraction and manufacture of materials (explaining
524 75% of the negative impact), rather than the direct use of energy (25% of the impact). Moreover,
525 the fiber content in a car panel is half of that in an insulation board (40% versus 88%); therefore,
526 more additives (here, polypropylene) are required, resulting in a higher climate change impact:
527 605 kg CO₂-eq and 6,752 kg CO₂-eq per FU in the IB and CP scenarios, respectively. The lower
528 fiber content and increased polypropylene demand also lead to more car panels being produced
529 than insulation boards from 1 ha of land, i.e., 5.33 t versus 2.88 t, respectively (Tables A.S10
530 and A.S12). Therefore, even though thermoforming is adopted for manufacturing both the
531 insulation boards and the car panels, the emission from the car panel production is three times
532 that from the insulation production (3,638 kg CO₂-eq versus 1,092 kg CO₂-eq). Furthermore,
533 the fibers need to be spun into mats before being mixed with the polypropylene, which emits
534 5,788 kg CO₂-eq per FU as a result of energy consumption; this is especially important to
535 freshwater and marine eutrophication because of PO₄³⁻ and NO_x emissions, respectively, from
536 fossil fuels (e.g., coal and lignite) (Tables B.S51 and B.S52).

537 Fig. 4 also illustrates that, for the CP scenario, the weight reduction induced by the use of
538 hemp fiber, which implies a decrease in gasoline use, translates into environmental benefits (in
539 dark blue), with negative scores of 4.41%, 23.71%, 55.55%, and 31.4% for climate change,
540 non-cancer human health effects, and freshwater and marine eutrophication impacts,
541 respectively. The energy consumption in the matting process is responsible for positive impacts
542 to these four impact categories. At the end of life, because one-third of car panels are incinerated,

543 the generated heat substituting for marginal heat allows for benefits in all four impact categories,
544 in particular accounting for 18.19% of the negative score in freshwater eutrophication.

545 The use of a lime binder for the hemp concrete is responsible for a high amount of GHGs
546 (7,637 kg CO₂-eq per FU) as a result of limestone decomposition and the fuel (e.g., coal and
547 heavy fuel oil) needed to produce the binder (Table B.S23). This emitted CO₂ in the production
548 stage is not 100% compensated for in the use stage by material carbonation (Andersson et al.,
549 2013). In the IB and CP scenarios, CO₂ bound in the use stage corresponds to half of the GHG
550 emission from the binder production (-4,667 kg CO₂-eq per FU). Here, we considered a 100%
551 return of the hemp concrete carbon at the end of life, hence its overall net positive score (6,598
552 kg CO₂-eq per FU from manufacture to concrete disposal). Today, the most common disposal
553 practice for concrete is landfilling (Pretot et al., 2014). Here, slow biomass decay is assumed;
554 if no decomposition were to be considered, hemp concrete could have a net negative score (Ip
555 and Miller, 2012; Sinka et al., 2018), contributing to climate mitigation in the future (Lecompte
556 et al., 2017).

557 Avoiding the initial CV-land management results in positive emissions in climate change
558 and freshwater eutrophication, primarily from indirect sources such as land use changes and
559 extra crops needed to compensate for the decreased production of ryegrass feed. With respect
560 to marine eutrophication, the maize and soybean cultivated to compensate for the decreased
561 production of ryegrass require less nitrogen fertilizers than ryegrass; therefore, avoiding
562 ryegrass cultivation reduces emissions from nitrogen fertilizers in all three scenarios (Fig. 4d).

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564 **3.3. Dynamic LCA**

565 Fig. 5 shows the GMTC calculated over 250 years under the three scenarios for the non-
566 biogenic, biogenic, and total GHG emissions (SI. C). Hereafter, biogenic GHGs are those
567 associated with the foreground system, including CO₂ captured by hemp, CO₂ emitted from the

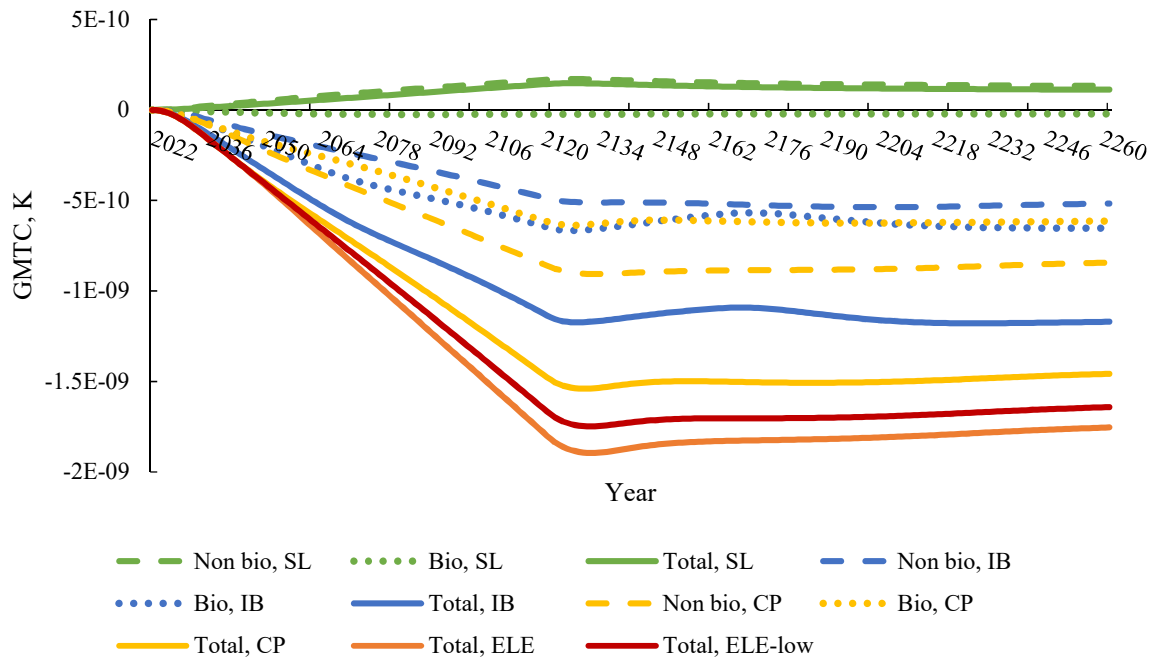
568 hemp biomass over the entire considered period (in manufacturing, decomposition, and end of
569 life), and CH₄ and N₂O emissions related to the biomass (e.g., CH₄ emitted during landfilling).
570 All other GHG flows, including replaced or induced production, were attributed to non-biogenic
571 sources (e.g., carbon from the induced biomass used as feed to compensate for the loss of silage
572 ryegrass). Negative values indicate a mitigation effect (a temperature decrease).

573 Both the IB and CP scenarios show a net negative trend. The GMTCs from both the
574 biogenic and non-biogenic GHGs decrease continuously during hemp cultivation and become
575 nearly flat for the next 150 years. The negative GMTC of the non-biogenic flows is primarily
576 due to avoided production, e.g., glass wool insulation boards and glass car panels, which is
577 consistent with the static LCA results. Details concerning the results for the analyzed GHGs are
578 given in SI. C. In the short term, the GMTC associated with the non-biogenic CO₂ flow is
579 positive in the CP scenario because of emissions resulting from induced production
580 corresponding to intensive grassland and rapeseed land. The GMTC then decreases gradually
581 with the implementation and perpetuation of the hemp value chain, becoming negative in 2038
582 and reaching its lowest value after the end of life of the final hemp car panel as a result of the
583 avoided glass car panel production and the saved gasoline. The GMTC from CH₄ reaches its
584 lowest value in 2124 and then increases because the CH₄ emission from the counter-flow ends
585 at this time with the end of cultivation; CH₄ from panel disposal (both incineration and
586 landfilling) is continuously released. The situation for the captured CO₂ from avoided gasoline
587 is opposite because part of the avoided gasoline is made from bioethanol; therefore, the CO₂
588 absorbed by the bioethanol-related biomass is eliminated, resulting in a negative CO₂ flow and
589 a rising temperature. Captured CO₂ is one of the main contributors to the negative non-biogenic
590 GMTC because of the important contribution of the induced biomass cultivation for forage
591 production. Because of the long timespan of CO₂ in the atmosphere, after the final car panel is
592 disposed of, the GMTC caused by the absorbed CO₂ remains negative. The main contributor to

593 the non-biogenic negative GMTC is the carbonation of concrete during its use stage. In both
594 the IB and CP scenarios, non-biogenic CO₂ is the most critical GHG for climate mitigation; the
595 negative GMTC decreases rapidly during the years in which hemp is growing and then slows
596 down after all the hemp is converted into insulation boards or car panels because the GMTC is
597 primarily linked to avoided production. In the case of the biogenic flows, CO₂ and CH₄
598 emissions lead to an increase in the GMTC, primarily arising from above-ground residue
599 decomposition and the landfilling of products, respectively. The CO₂ captured during
600 cultivation reduces the GMTC drastically, leading to a decreasing trend for the total biogenic
601 flow. Noticeably, in the biogenic flows, the quantity of CO₂ captured by hemp and the CO₂
602 emitted do not exactly match because of the actual type of disposal considered here (15.88%
603 decomposition rate in landfilling over 100 years) (IPCC, 2019). For example, in the IB scenario,
604 for the hemp cultivated in 2022, 83.7% of the carbon in the harvested straw is stored in the
605 technosphere in 2024 as hemp concrete and insulation boards. The insulation boards would then
606 be landfilled in 2064 after 40 years of use; meanwhile, there is no decomposition of the hemp
607 concrete. In 2163, the emission from landfilling is assumed to be complete and 78.4% of the
608 carbon from the initially harvested straw is stored in the technosphere in the IB scenario.
609 Similarly, 70.8% of the carbon from the harvested straw is stored in the technosphere in the CP
610 scenario; the small difference in the negative emissions between the IB and CP scenarios
611 explains why the longer carbon delay effect of the insulation boards (because of their longer
612 lifespan) is not significant. Three major carbon pools exist in the IB and CP scenarios, e.g., the
613 hemp insulation, fiber car panels, and shive-based concrete; meanwhile, there is no such
614 anthropogenic carbon pool in the SL scenario. The negative values of both the non-biogenic
615 and biogenic flows lead to overall negative GMTCs in the IB and CP scenarios, even though
616 the years with the lowest GMTC are slightly different for the two scenarios as a result of the
617 continuously avoided gasoline in the CP scenario and the difference between the lifespans of

618 the products (hemp insulation boards versus car panels). According to the consequential LCA
619 results, the avoided GHG emission is higher for glass car panels (plus the saved gasoline) than
620 for glass wool thermal insulation. Indeed, with the lower GMTC of its non-biogenic flow (but
621 similar biogenic flow), the CP scenario could mitigate global warming better than the IB
622 scenario. If the results are extrapolated from 1 ha to the total area of CV land in France (e.g.,
623 2,400,000 ha; Shen et al., 2022), cultivating hemp instead of the initial vegetation in the IB and
624 CP scenarios leads to a potential decrease in the global mean temperature with respect to the
625 business-as-usual situation in 2100 of 0.0022 °C and 0.0028 °C, respectively. At the end of the
626 system, around the year 2262, the global mean temperature decreases are still 0.0028 °C and
627 0.0035 °C for the IB and CP scenarios, respectively.

628 In the case of the SL scenario (Fig. 5), the non-biogenic flow increases the temperature in
629 the first 100 years as a result of agricultural management and the hemp oil extraction, similar
630 to the IB and CP scenarios; however, here, the avoided products, e.g., palm oil and meal, cannot
631 compensate for this increase. Another important source of non-biogenic flows is the induced
632 products; the positive GMTC indicates that it is not wise to produce hemp oil rather than
633 ryegrass feed and rapeseed oil in the future. When the straw is left on the ground, carbon is
634 released in the short term after harvesting and the lack of an anthropogenic carbon pool (in
635 contrast with the IB and CP scenarios) deprives this scenario of a mitigation capacity. However,
636 the GMTC resulting from the biogenic flow is still slightly negative, indicating that hemp has
637 a better carbon capture capacity than the initial vegetation and that the enhanced SOC stock
638 contributes to the negative biogenic flow. Because of SOC saturation, the SOC increases are
639 modest with time (Fig. 3), affecting the biogenic flow, which becomes stable prior to the end
640 of the cultivation period. The SL scenario did not reach a negative GMTC within the studied
641 time period, and, when all French CV-land area is considered, this scenario would increase the
642 temperature by 0.000168 °C in 2262.



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644 **Fig. 5.** Dynamic global mean temperature change (GMTC) resulting from the biogenic (bio)
 645 and non-biogenic (non-bio) flows for the SL, IB, and CP scenarios and the sensitivity CP sub-
 646 scenarios, where electric mobility is considered from 2040 with 42% photovoltaic in the
 647 electricity mix (ELE) or 12% photovoltaic in the electricity mix (ELE-low) (described in
 648 Section 3.4.2). biogenic: related to the hemp; non-biogenic: related to all other processes.

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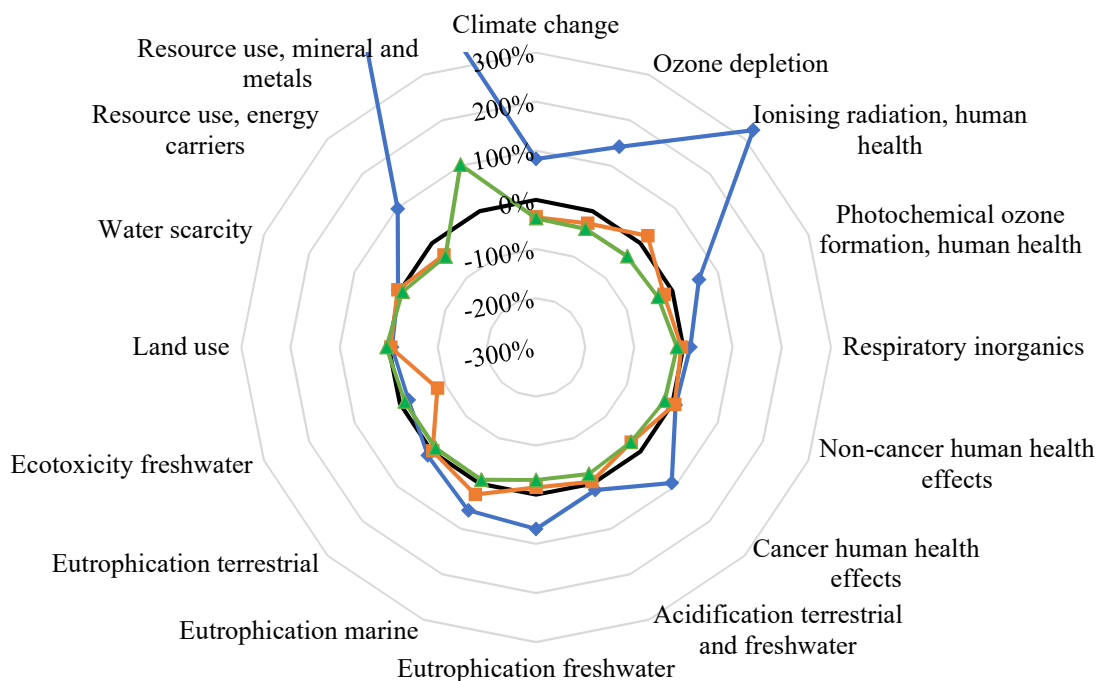
650 3.4 Sensitivity analysis

651 3.4.1 Consequential LCA

652 Not using (nitrogen) fertilizers implies that all fertilization-related emissions do not occur,
 653 i.e., mainly N_2O , NO_x , and NH_3 to air and nitrate losses to water; in addition, emissions from
 654 fertilizer production make significant contributions to most categories (according to the
 655 contribution analysis in SI. B). Furthermore, the lack of fertilizers leads to a lower yield,
 656 therefore decreasing the energy and material consumption in manufacturing. However, the
 657 reduced yield reduces the number of bio-based products produced and petrochemical products
 658 replaced, which is an important determinant of the environmental performance for most impact
 659 categories (Fig. 4). From Fig. 6a, the impact of mineral and metal resource use is, for all

660 scenarios, the impact most affected by a change from conventional fertilization to zero-
 661 fertilization. This is caused by the sliver ore ($1.5 \times 10^{-5}\%$ Ag and $5.4 \times 10^{-4}\%$ Au) used in the
 662 fertilizer lifecycle (all scenarios) and titanium and strontium, resulting from the lower share of
 663 avoided gypsum in the IB and CP scenarios and glass fiber in the CP scenario, respectively..
 664 Fig. 6a shows that, for scenario SL, using no fertilizer benefits all impacts except the freshwater
 665 ecotoxicity and the land use. For example, with respect to climate change, the fact that there is
 666 no emission from fertilizer production and use (e.g., N_2O) heavily compensates for the lower
 667 hempseed oil and meal production and substitution. . For the IB scenario, zero-fertilization
 668 benefits 5 (out of 16) impacts, and for the CP scenario, it benefits only 2 impacts. The SL
 669 scenario benefits from the lower emission associated with less fertilization; however, in the IB
 670 and CP scenarios, this benefit cannot compensate for the reduction in the advantages associated
 671 with the yield and the substituted petrochemical products. Therefore, zero-fertilization could be
 672 a compelling alternative for straw left on the ground; however, if the straw is intended for use
 673 in the technosphere, the yield benefit tends to compensate for trade-offs associated with
 674 fertilizers.

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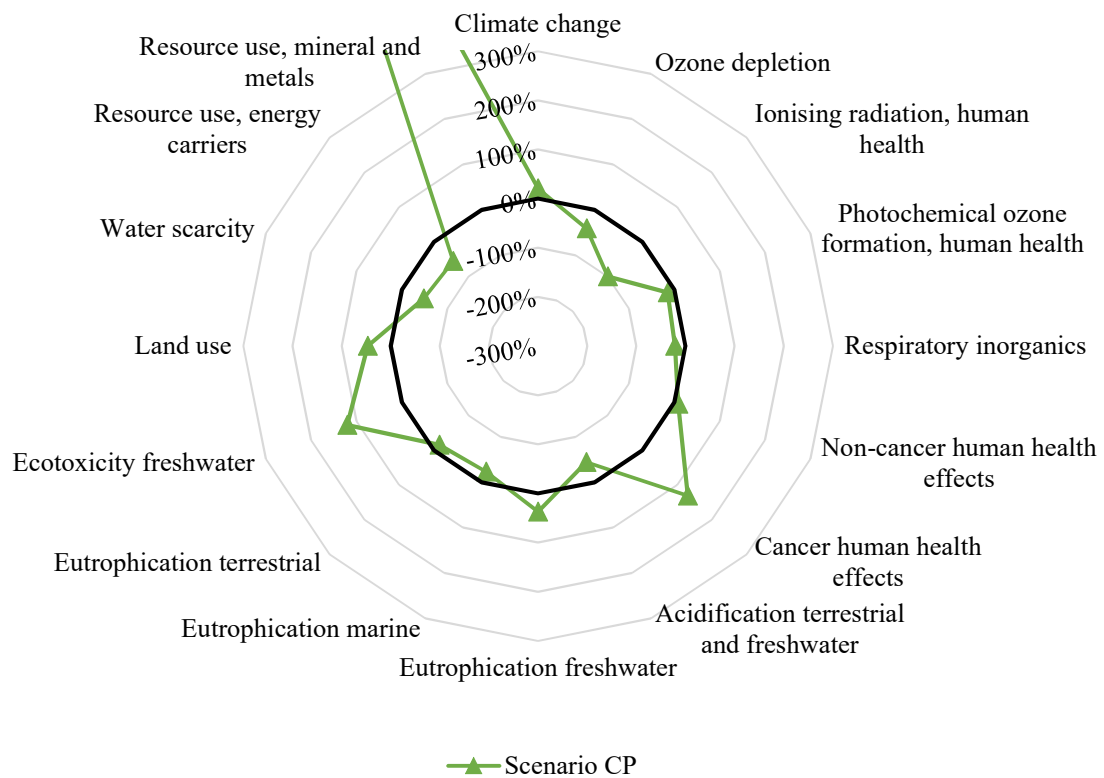
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698 **Fig. 6.** Sensitivity analysis portraying the relative changes observed for all impact categories
699 with respect to the baseline scenarios resulting from (a) zero-fertilization and (b) electric car
700 use after 2040 (CP scenario only). The bold black line represents the initial baseline scenarios
701 (e.g., no change). The positive values represent an improvement [%] in the net impact compared
702 with the reference (bold line), while negative values represent the opposite.

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Similar to the zero-fertilization sensitivity analysis, mineral and metal resource use and cancer human health effects are two of the most sensitive impact categories with respect to the replacement of thermal cars with electric cars because of the metal used in photovoltaic panel production for photovoltaic electricity (Fig. 6b). For 9 out of 16 impacts, the sensitivity analysis indicates, as expected, an overall reduction in the benefits as gasoline is replaced by electricity. For climate change, this shift leads, however, to a slight improvement in the impact. This is in

710 part due to the high GHG emissions occurring in photovoltaic panel production and in part
711 because gasoline contains a share of bioethanol (based on the used LCI dataset). According to
712 this situation, the performance of electric vehicles with respect to global warming needs to be
713 further investigated, not only in light of revised inventories for photovoltaic electricity but also
714 in light of eventual different electricity mixes in the specific case of France (e.g., a mix of only
715 wind power and hydropower after 2060; Kassara et al., 2019). Moreover, note that this
716 sensitivity analysis was performed on the basis of a simple substitution of a certain amount of
717 energy from gasoline to energy from electricity, without considering the differences in terms of
718 the performance between thermal and electric cars.

719 **3.4.2 Dynamic LCA**

720 Because electricity is predicted to be a determining factor in the future car market, the
721 influence of consuming electricity instead of gasoline is dynamically analyzed here. The
722 generic trends are similar between scenarios with only gasoline cars and the scenario with
723 electric cars after 2040 (Fig. 5, Total, ELE); however, the GMTC is even more negative for the
724 ELE scenario, indicating, as observed with the static LCA, that avoiding electricity is more
725 beneficial for climate change than avoiding gasoline. Indeed, as discussed in Section 3.4.1, this
726 is due to the marginal gasoline market and the electricity mix in France in the future based on
727 the Ecoinvent database. Accordingly, an electricity mix with a lower photovoltaic electricity
728 proportion (11.92% absolute value for 2050 based on the European Commission (2016); versus
729 42% in the baseline, being the marginal value calculated from the same dataset), was taken as
730 an additional sensitivity to be analyzed (Fig. 5, Total, ELE-low). This scenario still has a more
731 negative GMTC than gasoline, this time as a result of electricity derived from natural gas. The
732 manner in which electricity is produced is pivotal in the CP scenario. These results show the
733 promising performance of the CP scenario for climate mitigation in the future. However, it is
734 difficult to foresee the effect of replacing the energy source for cars during this time period.

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3.5. Uncertainty analysis

According to the contribution analysis shown in Fig. 4 (detailed in SI. B), 11, 12, and 14 parameters were selected for the GSA for the SL, IB, and CP scenarios, respectively (Fig. 7; Tables A.S24–S26). The uncertainties in the SL and IB scenarios stem from five main parameters (but not the same ones), and that in the CP scenario from three parameters. These parameters together explain at least 90% of the system uncertainty for a given scenario. The hemp yield is identified in all three scenarios and could be representative in most impact categories (Fig. 7). Furthermore, parameters related to the initial vegetation, including P2, P3, and P4, greatly affect the SL scenario. Since replacing the petrochemical products plays a key role in the environmental performance of the IB and SL scenarios, the avoided petrochemical products are also crucial in the uncertainty results (P12 and P14 in the IB and CP scenarios, respectively). Within the manufacturing processes (Fig. 1) of the CP scenario, matting is more significant than mixing in the contribution analysis; however, mixing represents more uncertainty than matting for all impact categories represented in Fig. 7 (P14 indicates the polypropylene amount used in the mixing process).

For climate change and freshwater and marine eutrophication, the results indicate that the CP scenario is unequivocally better than the IB scenario, which is better than the SL scenario (Fig. 7). For the impact on the non-cancer human health effects, the results of the SL and IB scenarios cannot be differentiated. Similarly, it is difficult to conclude whether there are differences between the scenarios for the impacts on cancer human health effects, freshwater ecotoxicity, water scarcity, and mineral and metal resource use, as shown in the Fig. B.S118.

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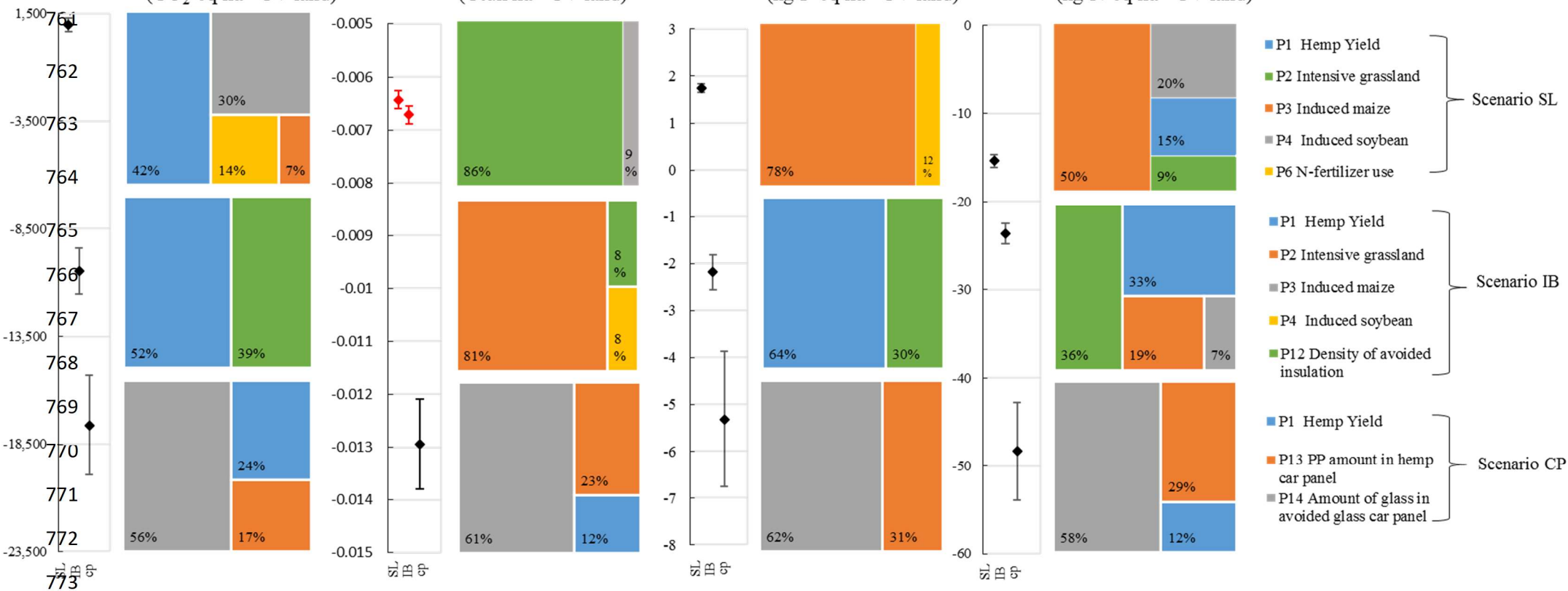
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Climate change
(CO₂-eq ha⁻¹ CV-land)

Non-cancer human health
(Ctuh ha⁻¹ CV-land)

Freshwater eutrophication
(kg P-eq ha⁻¹ CV-land)

Marine eutrophication
(kg N-eq ha⁻¹ CV-land)



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775 **Fig. 7.** Uncertainty analysis of the climate change, non-cancer human health effects, and freshwater and marine eutrophication impact categories.
776 The overall system uncertainty is represented on the left-hand side, while the contributions of all the identified sensitive parameters to the system
777 uncertainty are represented on the right-hand side. Red denotes overlap, indicating that the result is inconclusive.

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780 **3.6. Overall implications, limitations, and perspectives**

781 According to the results of the consequential static LCA for climate change, the mitigation
782 effectiveness of hemp-product scenarios replacing conventional materials is larger than the
783 effect of negative emissions (stemming from the carbon stored in anthropogenic products only
784 because no additional carbon is stored as SOC in these scenarios). The increased SOC storage
785 (negative emission) in the SL scenario cannot compensate for the lack of mitigation; the climate
786 benefit from the SOC increase in the SL scenario is equivalent to 10% and 4% of the climate
787 benefit of the avoided wool insulation and glass fiber car panels, respectively. The carbon in
788 hemp-based products was assumed to be completely emitted in the consequential static LCA;
789 therefore, the benefit of storing carbon in the technosphere was not reflected in this analysis.
790 Conversely, dynamic LCA allows the identification of time periods when carbon storage is
791 effective and gives a temporal dimension to the negative emissions: negative emissions
792 resulting from soil storage occur over the entire cultivation period (100 years), while negative
793 emissions resulting from carbon storage in anthropogenic products last for a longer period, e.g.,
794 the cultivation period plus the lifetime of the products. Shares of 78.4% and 70.8% of carbon
795 from the harvested hemp straw were shown to be stored in the IB and CP scenarios, respectively.
796 Together with the net SOC changes, this could contribute to a temperature decrease (GMTC)
797 of 0.00157 °C and 0.00147 °C, respectively, in 2262 (reductions from the biogenic flows if all
798 French CV land were to be cultivated with hemp). In the case of the IB scenario, the level of
799 GMTC for the biogenic flow (e.g., SOC and the technosphere sinks) is similar to that resulting
800 from non-biogenic sources (determined by the product replacement). The CP scenario shows a
801 similar trend but a larger contribution to the total GMTC from the non-biogenic flow (60%
802 versus 40% for the biogenic flows). This result indicates that both the negative emissions and
803 the GHG reductions from mitigation are important for controlling climate change and that their

804 effects remain important for a long time. Finally, both static and dynamic LCA result in the
805 same scenario rankings for the climate change impact (the CP scenario is better than the IB
806 scenario, which is better than the SL scenario).

807 As previously mentioned, using hemp as CSAAP may not benefit climate change and other
808 environmental impacts in the SL scenario. One possible reason is that intensive grassland can
809 store a larger amount of carbon in the soil; therefore, its replacement would induce additional
810 forage production and land use changes that emit large quantities of GHGs. Therefore, the type
811 of land cover on the selected CV-land may need to be reconsidered (e.g., mobilizing a lower
812 share of intensive grasslands). However, this factor did not impact the actual CSAAP scenarios
813 (the IB and CP scenarios). In the land selection, explained in a previous work (Shen et al., 2022),
814 the criterion of non-competition with food demand was considered. Moreover, the potential
815 feed from initial vegetation (e.g. from intensive grassland) is included in the consequential LCA
816 (Fig. 1) as a missing product from the hemp cover. In this way, the induced feed production by
817 any competing land use is included in the system modelling.

818 The replacement of petrochemical products by hemp-based products contributes heavily
819 to the overall environmental performance in both the static and dynamic LCAs. Yet, one might
820 question to what extent there is an actual demand for these products, particularly given the
821 expected advancement in recycling technologies and re-use practices in the future. For example,
822 using all CV land in France, 5,114,840 t of hemp fiber could be produced in one year. However,
823 only 80,000 t of natural fibers (including wood and other plants) are actually used in the
824 European car industry each year (European Commission, 2018). Similarly, the production of
825 insulation boards from all CV land in France could be as much as 230,102,600 m³ year⁻¹,
826 representing as much as 85% of the total European demand (269,300,000 m³ in 2019; Pavel
827 and Blagoeva, 2018) and 21% of the world demand estimated for 2028 (1,098,600,000 m³
828 year⁻¹; Fortune Business Insights, 2022; Pavel and Blagoeva, 2018). In addition to market

829 limitations, a hemp monoculture on all CV-land for a period of 100 years of continuous
830 cultivation may not allow maintaining a stable yield, as assumed in this study. In France, hemp
831 is typically grown in rotation with a winter cereal, often wheat (Terres Inovia, 2016). This
832 allows for reducing diseases and weeds. On the other hand, Gorchs et al., (2017) concluded
833 from a comparison of hemp grown in monoculture versus hemp grown in rotation with wheat
834 that hemp could be grown for several years in monoculture without yield decline. Nevertheless,
835 the uncertainty analysis highlighted the importance of yield for the overall uncertainty of the
836 scenario results (explaining the uncertainty from 24% to 52%, according to the scenario; Fig.
837 7). Hence, in a decision-making perspective, the results presented in this study should be seen
838 as optimistic, and future work could seek to define a yield threshold ensuring the overall
839 environmental performance of the product scenarios studied herein. In addition, it should be
840 highlighted that the CV-land area is larger than the existing hemp cultivation, at 2,400,000 ha
841 versus 18,000 ha in 2018 (Raymunt, 2020; Shen et al., 2022) and hemp may not be capable of
842 growing in all of these areas. Our extrapolation exercise from 1 ha to all CV-land is therefore
843 only intended to highlight the order of magnitude of the possible biomass and products
844 generation and the climate benefit attainable from CV-land use; it does not mean that all CV-
845 land can or should be used in this manner.

846 This study focused on annual plants; however, the performances associated with perennial
847 species because of their ability to stock carbon in the soil (Dobbratz et al., 2021) may be more
848 interesting and should be investigated in future studies.

849

850 **Conclusions**

851 This study analyzed the CSAAP concept based on hemp cultivated on CV land in France.
852 Three utilization scenarios were investigated, differing in the product lifetime in the
853 technosphere, i.e., no carbon storage (the SL scenario) or storage in two products with one being

854 considered as an infinite sink in the technosphere (hemp cement) and the other having a shorter
855 lifetime (car panels in the CP scenario with a lifetime of 10 years and thermal insulation in the
856 IB scenario with a lifetime of 40 years). CV-land use change via cultivating hemp (replacing
857 the current land cover type) with no utilization in long-lived products (the SL scenario) cannot
858 mitigate climate change despite the negative emissions induced in the soil. Conversely, biomass
859 utilization in long-lived products (the CP and IB scenarios) acts as an additional negative
860 emission via the technosphere, complemented by GHG mitigation via the displacement of
861 conventional fossil-based products. However, no additional sequestration in the SOC pool
862 could be obtained using these scenarios. This tendency is not the same as those of other impact
863 categories, for example, water scarcity is increased in all scenarios indicating that, with respect
864 to water scarcity, it is better to maintain CV-land with its initial vegetation rather than to
865 cultivate hemp. With respect to freshwater and marine eutrophication, the CP scenario is
866 unequivocally presenting a higher environmental performance than the IB scenario, itself more
867 performant than the SL scenario. For other impacts, such as cancer human health effects,
868 freshwater ecotoxicity, water scarcity, and mineral and metal resource use, the results are
869 inconclusive.

870 This study assumed that all carbon captured through photosynthesis is emitted at the end
871 of life; therefore, the negative emission resulting from storage in anthropogenic products is
872 revealed by the delay of this release in the dynamic calculation but is not shown in the static
873 LCA. In the long-term, the technosphere was shown to be a larger carbon sink than the soil for
874 negative emissions. Mitigating GHG emissions (in other words, the choice of the avoided
875 products and activities) could play a determining role in the ranking of scenarios and definitely
876 discriminates between the IB and CP scenarios, while making the SL scenario unsuitable for
877 climate mitigation. While this study proved the feasibility of using hemp as CSAAP, this
878 theoretical approach requires validation via experiments and simulations for more varied

879 conditions such as local land conditions, the agricultural practices to be used (e.g. rotations,
880 fertilization), and the use of bio-materials in a large variety of products.

881

882

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890

891 **Appendix A. Supplementary data**

892 Three supplementary data are attached to this paper.

893 Supplementary data A (SI. A) contains the inputs of all of the models, including the AMG
894 model, the LCA inventory, the GHGs in the dynamic LCA, and the parameters in the
895 uncertainty analysis.

896 Supplement data B (SI. B) presents the LCA results, including the scores, contribution
897 analyses, and uncertainties of all impact categories.

898 Supplementary data C (SI. C) presents the GHG flows considered in the dynamic LCA
899 every year and the GMTC results according to the GHG.

900

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