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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

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

* corresponding author

Abstract

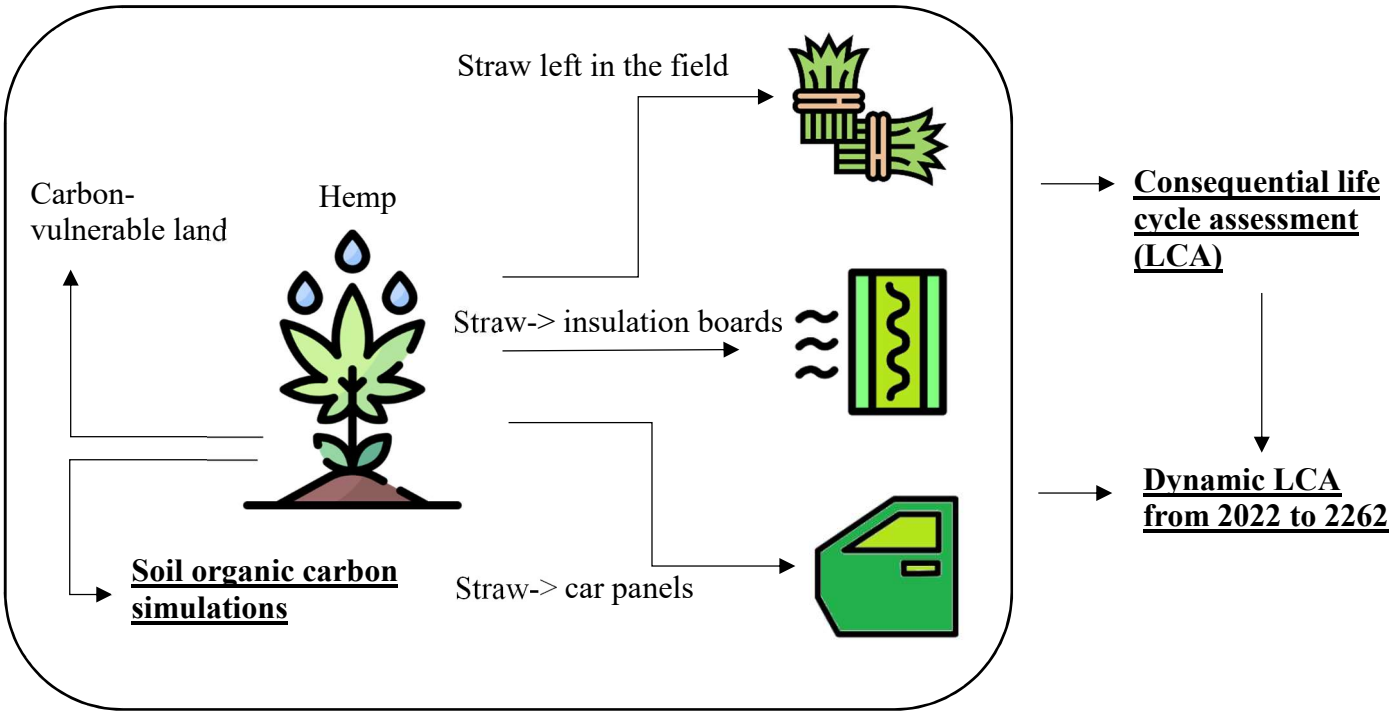
In this study, the potential of carbon storage in soil combined with mitigation via bio-based products is investigated for the case of 100 years of hemp cultivation on carbon-vulnerable land (CV-lands) in France. The originality of this study lies in the coupling of soil organic carbon (SOC) simulations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

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

Highlights

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

Graphical Abstract



1 Introduction

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

Unlike most fiber crops (e.g., flax), additional carbon storage in the SOC pool has been observed during hemp cultivation. Previous studies have reported that 100–300 kg CO_2 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 CO_2 and 1.19 million m^3 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

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

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

2 Methods

2.1 Overview of the step-wise approach

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

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

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

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

The 100-year SOC evolution associated with these three CV-land management types, and that with hemp cultivation (with and without straw harvest), were quantified using the AMG soil simulation model (detailed in Clivot et al., 2019) and calibrated to estimate the topsoil (<30 cm) SOC changes under hemp cultivation conditions in France. Inputs to the AMG model include meteorological data (mean yearly temperature, precipitation, and evapotranspiration), soil characteristics (clay and rock percentage, C/N ratio, and topsoil depth), agricultural management (tillage type and depth and amount of water supplied via irrigation), and carbon input from both biomass (above and below ground) and other eventual sources (e.g., manure 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 ha^{-1} $year^{-1}$ 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

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

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

1) In the SL (straw left on ground) scenario, only the seeds are harvested, with 50 kg (fresh weight) of the harvested seeds being re-sown in the next rotation (Ventura and Kiess, 2015) and the remaining 925 kg of seeds being used to extract 296 kg of hemp oil, replacing the production of the same amount of palm oil. The seed meal after oil extraction is used for animal feed, thereby replacing marginal feed ingredients. The corresponding substitution in terms of avoided soybean meal, maize, and palm oil was calculated based on the methodology presented in Tonini et al. (2016). The hemp oil is assumed to be consumed in the year following its production, and all carbon in the oil is assumed, for tractability, to be emitted as CO_2. The hemp straw is left to decay on the ground.

2) In the IB (insulation board) scenario, both the seeds and the straw are harvested. The harvested seeds go through the same pathway as in the SL scenario. The harvested straw is then processed for fiber separation. In addition to fiber (circa 30% of the straw DM), shives (65%) are obtained as a by-product with lower economic value and the remaining 5% is lost as dust (Norton et al., 2009). Shives can be further mixed with lime and water to produce hemp concrete, which is considered in this scenario (with proportions of 17.8% shives, 32.9% lime, and 49.3% water for 1 m^3 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 CO_2 via a carbonation mechanism. Here, based on Pretot et al. (2014),
235 we assumed that 77 kg CO_2 is absorbed per m^3 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 Section2.8. 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 CH_4 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 CO_2 and 13% as CH_4) 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 CH_4, while the rest would be emitted as CO_2.
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

material allows vehicles to have a lower fuel consumption compared with vehicles using conventional glass fiber panels (Deng, 2014). Here, reduction of 2.35 L of gasoline per kg car panel was assumed over the lifetime of the panel (Section A.2.11). Based on Gueudet (2016), it was assumed that 30% of the hemp car panels would be incinerated with power recovery at the end of life, while 70% would be landfilled (no CH_4 recovery). Landfilling emissions were calculated in the same manner as in the IB scenario.

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

The system boundaries considered for the three scenarios are summarized in Fig. 1, and the corresponding inventory tables are available in the SI. A (Sections2.2–2.14). Background data (e.g., electricity, fertilizer production, and machines used in manufacturing) were primarily extracted from the Ecoinvent v3.5 consequential life cycle inventory database. Foreground data were estimated based on published literature and simulations, as described above.

On the basis of a recent European Commission Recommendation (EC, 2021), the Environmental Footprint v2.0 life cycle impact assessment method (Fazio et al., 2018), which assesses 16 impact categories, was used to evaluate the environmental impacts of the scenarios (Table A.S22). The LCA was implemented using the SimaPro software, version 9.1.1.

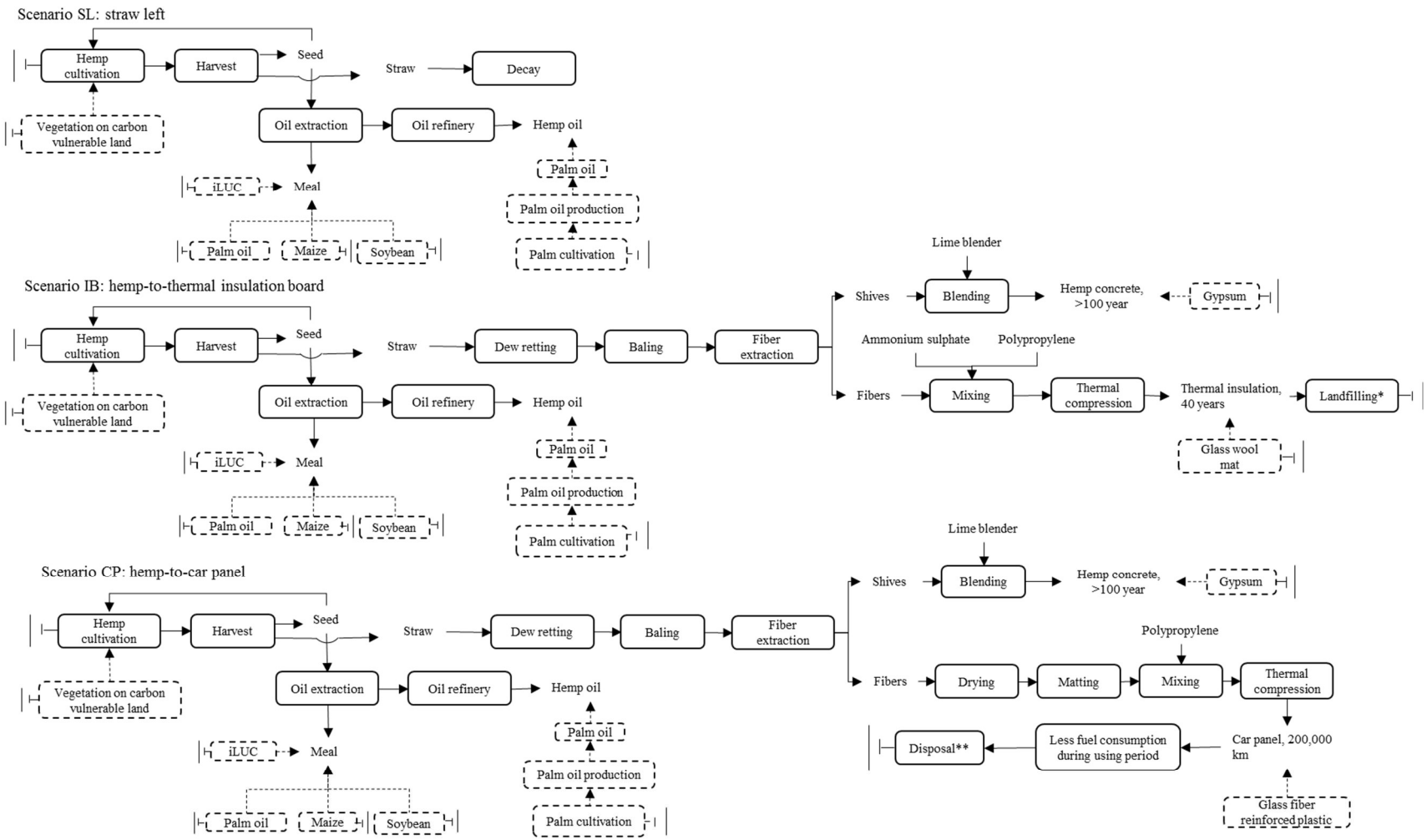


Fig. 1. Process flow diagram and system boundaries considered for the three assessed scenarios. The boxes indicate processes, with the solid lines indicating induced processes and the dotted lines indicating avoided processes. *Landfilling without CH_4 recovery. **30% of the car panel material is disposed of via incineration with power recovery, while the rest is disposed of via landfilling without CH_4 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 CH_4 and CO_2) 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).
344

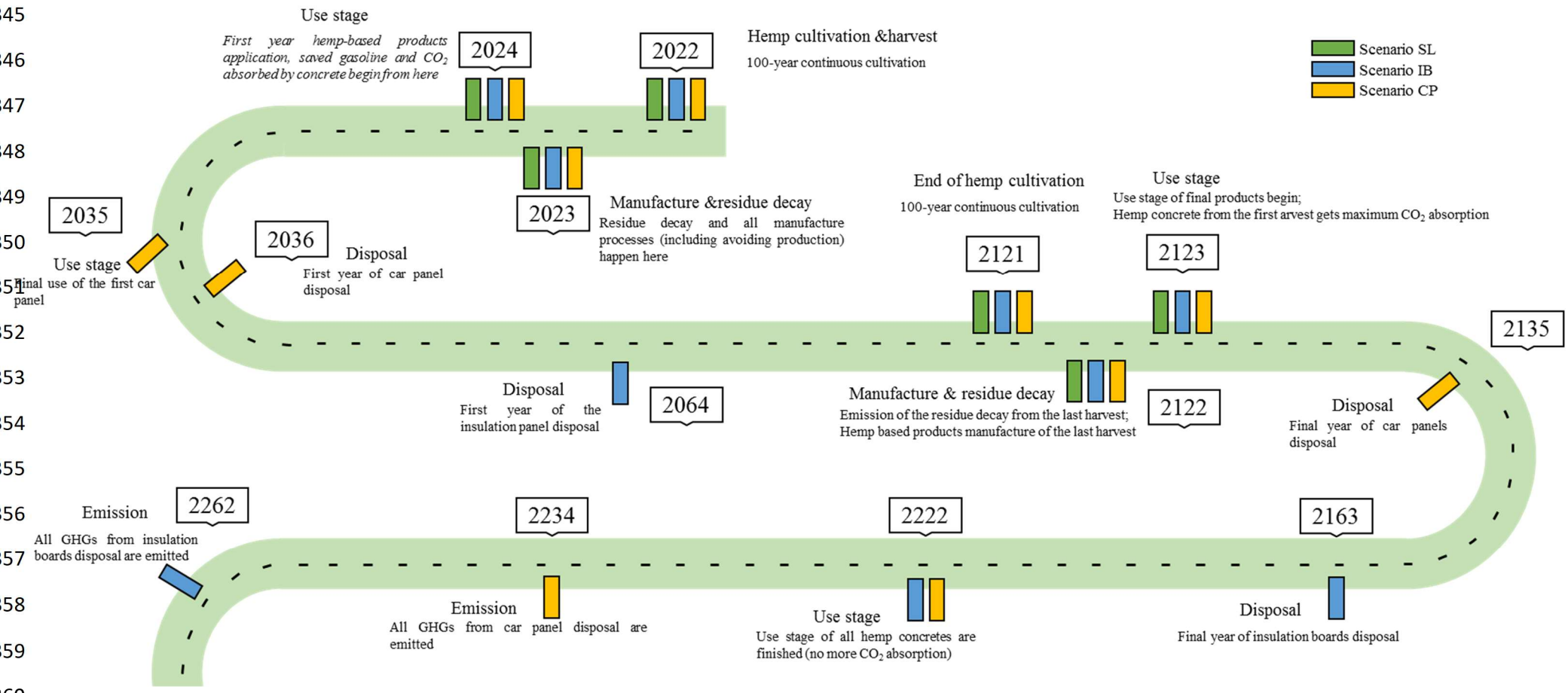


Fig. 2. Timeline considered in the dynamic life cycle assessment (LCA) for the three scenarios. In the SL scenario, in which the straw is left on the ground, "residues" refer to the entire straw, while in the IB and CP scenarios, in which the hemp fibers are used for insulation boards and car panels,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

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 N_2O
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 CO_2 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.
395

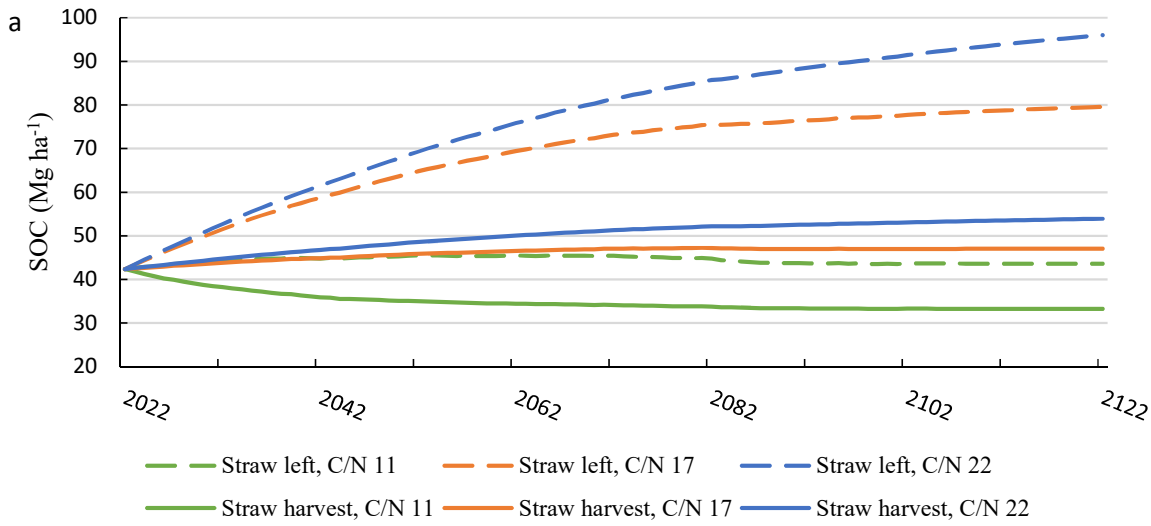
396 **3 Results and discussion**

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 -

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

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



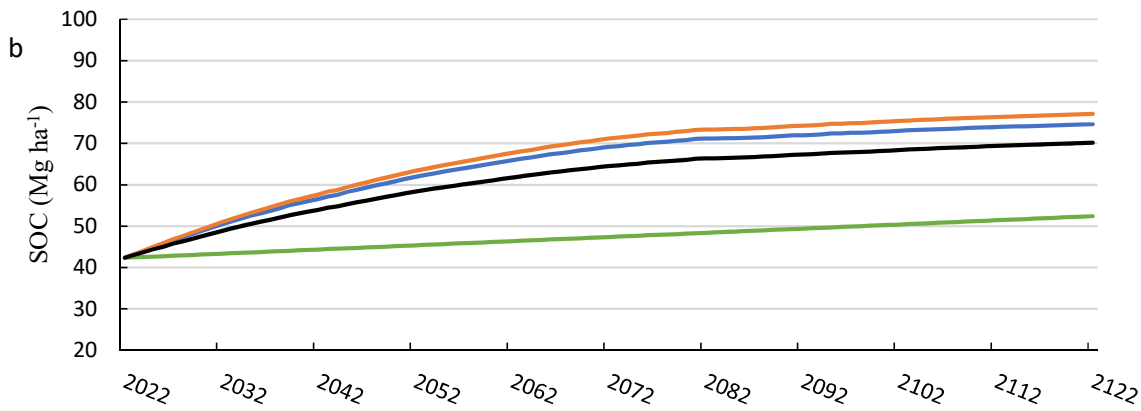


Fig. 3. Evolution of the 100-year soil organic carbon (SOC) stock (a) with different C/N ratios for hemp cultivation on average carbon-vulnerable (CV) land and (b) for the initial vegetation on the CV land with a C/N ratio of 17.

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 CO_2-eq ha^{-1}) and freshwater eutrophication (net 1.74 kg P-eq ha^{-1}).

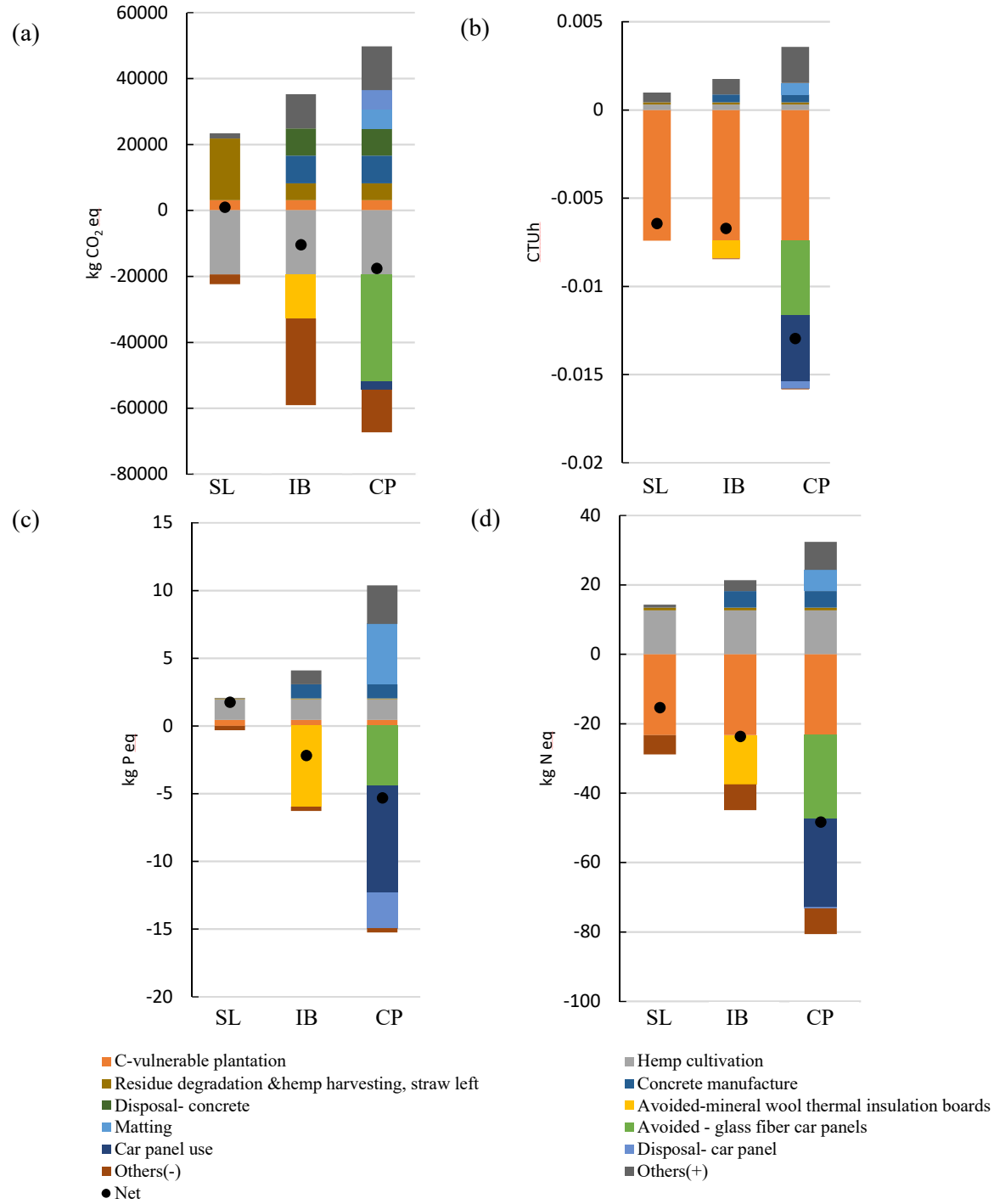


Fig. 4. Life cycle impact assessment results for (a) climate change, (b) non-cancer human health effects, and (c) freshwater and (d) marine eutrophication impacts with the breakdown per process contribution. For tractability reasons, only the most significant processes are depicted here. The breakdown categories "others (+)" and "others (−)" aggregate the remaining positive and negative contributions, respectively.

In the SL scenario, the soil in the 1 ha of CV land can store an amount of carbon equivalent to 1.35 t CO_2 (Fig. 3), which is greater than the net climate change result for this scenario. However, this SOC increase results in less carbon transported to downstream processes and higher CO_2 and N_2O emissions during residue decomposition (18.1 t CO_2 and 1.49 kg N_2O in the SL scenario and 4.81 t CO_2 and 0.46 kg N_2O in the IB and CP scenarios). In the IB and CP scenarios, because the straw is harvested, there is more straw carbon ending up in the technosphere than in the soil; therefore, the benefit from the SOC enhancement (−170 kg CO_2-eq) is smaller than that in the SL scenario.

Fig. 4 highlights the importance of the avoided petrochemical counterfactuals in the IB (mineral wool insulation boards; in yellow) and CP (glass fiber car panels; light green) scenarios for all impact categories. Avoiding wool-based boards is beneficial to climate change, non-cancer human health effects, and freshwater and marine eutrophication (−13.32 t CO_2-eq, −0.001 CTUh, −5.97 kg P-eq, and −14.17 kg N-eq per FU, respectively, which represents 29.12%, 11.84%, 94.9%, and 31.55% of the negative scores, respectively). The avoided car panels are also beneficial to the same impact categories (−31.96 t CO_2-eq, −0.004 CTUh, −5.97 kg P-eq, and −23.72 kg-N eq per FU, respectively, which represent 47.75%, 26.25%, 28.16%, and 29.4% of the negative scores, respectively). The high contribution of the avoided products means that the manufacturing of hemp-based materials performs better than the manufacturing of conventional materials, which is in agreement with previous studies (Ardente et al., 2008; Kim et al., 2008; Norton, 2008; Tadele et al., 2020; Zampori et al., 2013). Of course, these benefits exist as long as the substitution of petrochemical counterparts is possible, which seems to be the case for the upcoming 10 years (Grand view research, 2021, 2019). Considering that the time scale of this study is from 2022 to 2122, it is difficult to predict the development of the replaced products over such a long-term period; it is possible that, with the development of new

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

Compared with avoided wool-based boards, the negative climate change score of the avoided car panels is primarily due to the extraction and manufacture of materials (explaining 75% of the negative impact), rather than the direct use of energy (25% of the impact). Moreover, the fiber content in a car panel is half of that in an insulation board (40% versus 88%); therefore, more additives (here, polypropylene) are required, resulting in a higher climate change impact: 605 kg CO_2-eq and 6,752 kg CO_2-eq per FU in the IB and CP scenarios, respectively. The lower fiber content and increased polypropylene demand also lead to more car panels being produced than insulation boards from 1 ha of land, i.e., 5.33 t versus 2.88 t, respectively (Tables A.S10 and A.S12). Therefore, even though thermoforming is adopted for manufacturing both the insulation boards and the car panels, the emission from the car panel production is three times that from the insulation production (3,638 kg CO_2-eq versus 1,092 kg CO_2-eq). Furthermore, the fibers need to be spun into mats before being mixed with the polypropylene, which emits 5,788 kg CO_2-eq per FU as a result of energy consumption; this is especially important to freshwater and marine eutrophication because of PO_4^{3-} and NO_x emissions, respectively, from fossil fuels (e.g., coal and lignite) (Tables B.S51 and B.S52).

Fig. 4 also illustrates that, for the CP scenario, the weight reduction induced by the use of hemp fiber, which implies a decrease in gasoline use, translates into environmental benefits (in dark blue), with negative scores of 4.41%, 23.71%, 55.55%, and 31.4% for climate change, non-cancer human health effects, and freshwater and marine eutrophication impacts, respectively. The energy consumption in the matting process is responsible for positive impacts 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 CO_2-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 CO_2 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, CO_2 bound in the use stage corresponds to half of the GHG
550 emission from the binder production (−4,667 kg CO_2-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 CO_2-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).
563

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 CO_2 captured by hemp, CO_2 emitted from the

568 hemp biomass over the entire considered period (in manufacturing, decomposition, and end of
569 life), and CH_4 and N_2O emissions related to the biomass (e.g., CH_4 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 CO_2 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 CH_4 reaches its
584 lowest value in 2124 and then increases because the CH_4 emission from the counter-flow ends
585 at this time with the end of cultivation; CH_4 from panel disposal (both incineration and
586 landfilling) is continuously released. The situation for the captured CO_2 from avoided gasoline
587 is opposite because part of the avoided gasoline is made from bioethanol; therefore, the CO_2
588 absorbed by the bioethanol-related biomass is eliminated, resulting in a negative CO_2 flow and
589 a rising temperature. Captured CO_2 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 CO_2 in the atmosphere, after the final car panel is
592 disposed of, the GMTC caused by the absorbed CO_2 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 CO_2 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, CO_2 and CH_4
598 emissions lead to an increase in the GMTC, primarily arising from above-ground residue
599 decomposition and the landfilling of products, respectively. The CO_2 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 CO_2 captured by hemp and the CO_2
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.

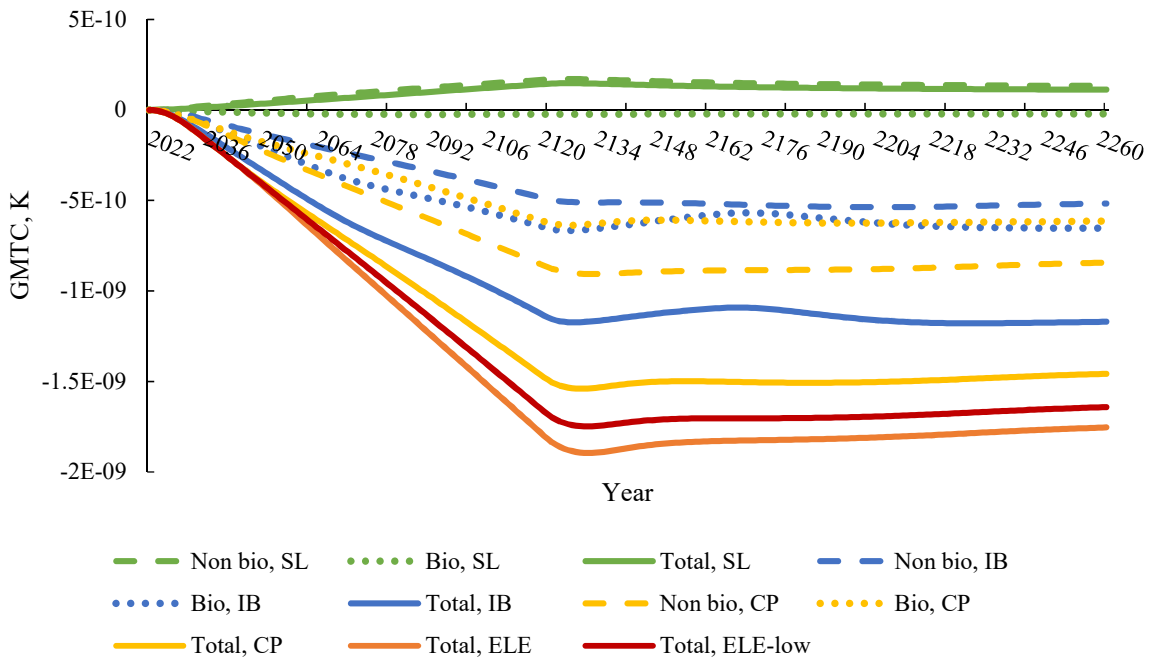


Fig. 5. Dynamic global mean temperature change (GMTC) resulting from the biogenic (bio) and non-biogenic (non-bio) flows for the SL, IB, and CP scenarios and the sensitivity CP sub-scenarios, where electric mobility is considered from 2040 with 42% photovoltaic in the electricity mix (ELE) or 12% photovoltaic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

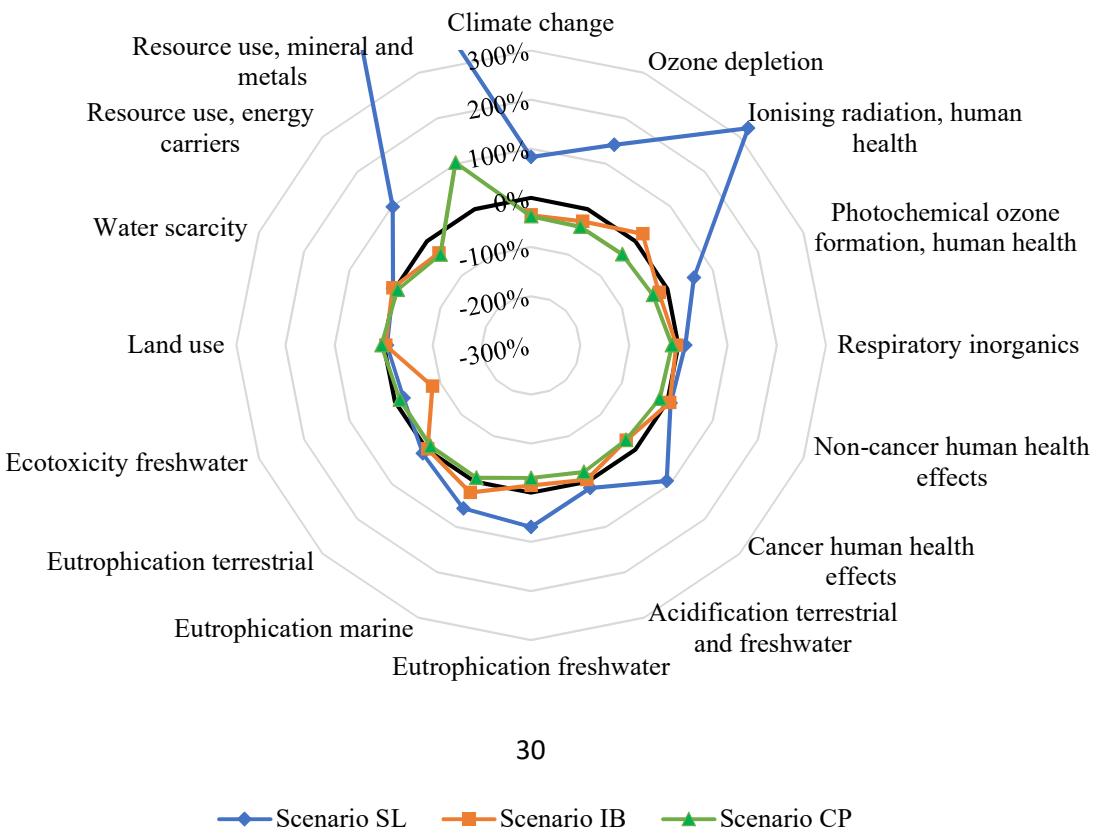
3.4 Sensitivity analysis

3.4.1 Consequential LCA

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

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

a



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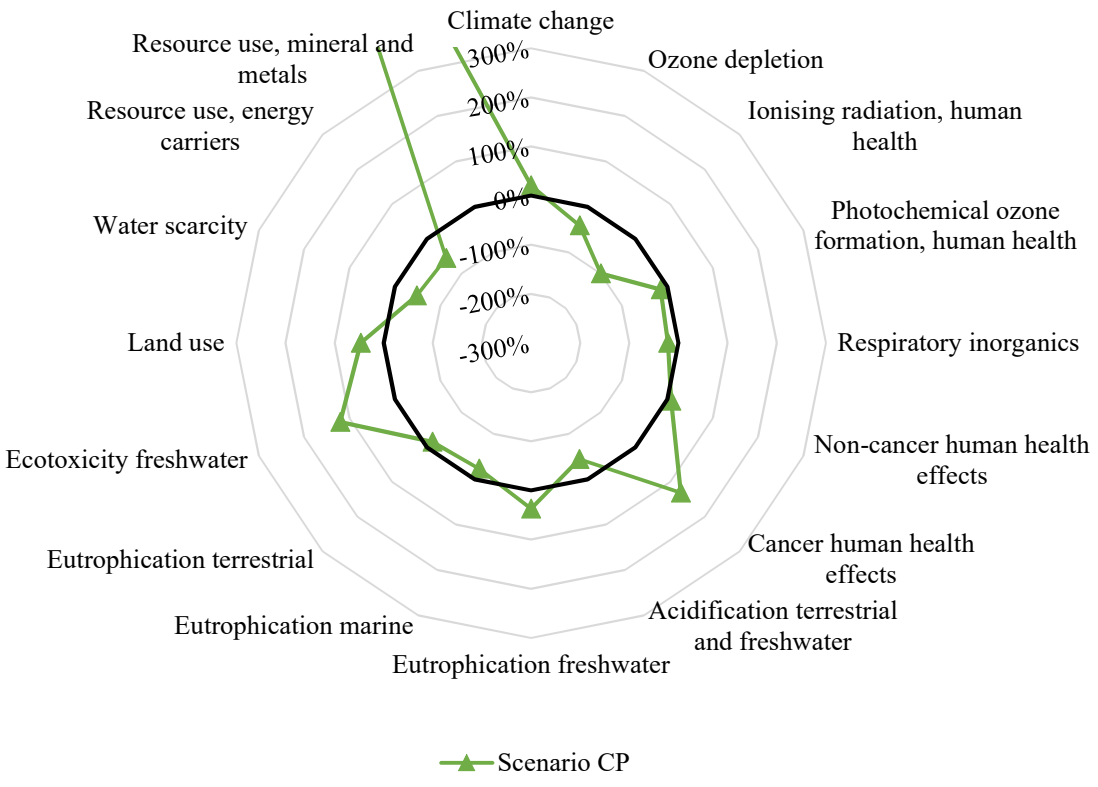

Fig. 6. Sensitivity analysis portraying the relative changes observed for all impact categories with respect to the baseline scenarios resulting from (a) zero-fertilization and (b) electric car use after 2040 (CP scenario only). The bold black line represents the initial baseline scenarios (e.g., no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

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.

735

736 **3.5. Uncertainty analysis**

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

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

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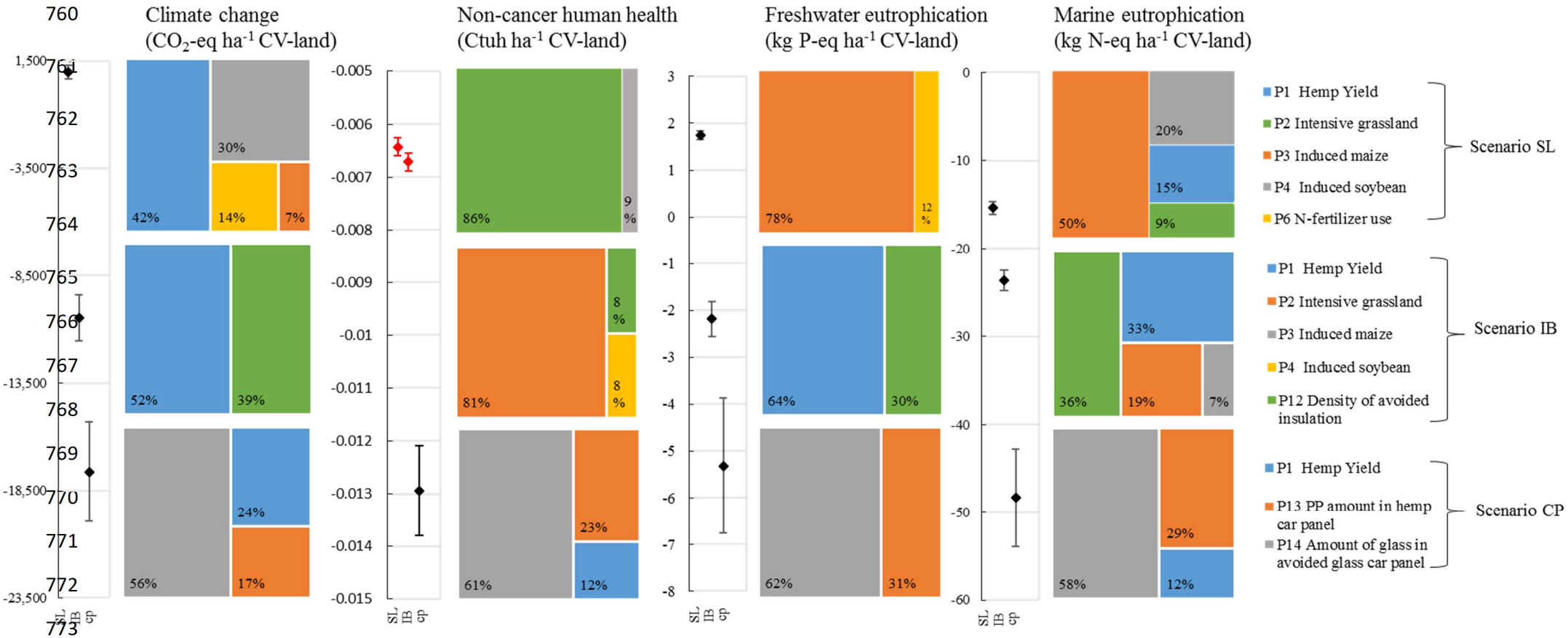

Fig. 7. Uncertainty analysis of the climate change, non-cancer human health effects, and freshwater and marine eutrophication impact categories. The overall system uncertainty is represented on the left-hand side, while the contributions of all the identified sensitive parameters to the system uncertainty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

3.6. Overall implications, limitations, and perspectives

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

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

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

The replacement of petrochemical products by hemp-based products contributes heavily to the overall environmental performance in both the static and dynamic LCAs. Yet, one might question to what extent there is an actual demand for these products, particularly given the expected advancement in recycling technologies and re-use practices in the future. For example, using all CV land in France, 5,114,840 t of hemp fiber could be produced in one year. However, only 80,000 t of natural fibers (including wood and other plants) are actually used in the European car industry each year (Euorpean Commission, 2018). Similarly, the production of insulation boards from all CV land in France could be as much as 230,102,600 m^3 $year^{-1}$, representing as much as 85% of the total European demand (269,300,000 m^3 in 2019; Pavel and Blagoeva, 2018) and 21% of the world demand estimated for 2028 (1,098,600,000 m^3 $year^{-1}$; Fortune Business Insights, 2022; Pavel and Blagoeva, 2018). In addition to market

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

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

Conclusions

This study analyzed the CSAAP concept based on hemp cultivated on CV land in France. Three utilization scenarios were investigated, differing in the product lifetime in the 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

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

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Appendix A. Supplementary data

Three supplementary data are attached to this paper.

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

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

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

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