Supplementary Material

Converting carbon vulnerable lands to wood plantations for use as building materials: overall environmental performance and time-dependent assessment of carbon dioxide removals.

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1 SOC simulation

Based on the rotation of black locust (*Robinia pseudoacacia* L.), the SOC change in the future 105 years (3 rotations) is investigated in this study. To simulate the SOC change in the future, C-Tool is adopted here. Temperature in the future is obtained from Drias(DRIAS les futurs du climat, 2014), which predicted the temperature from 2022 till 2100, from plots of the whole France, under a moderate scenario, RCP 4.5. The average of the predicted temperature in all plots is used on behalf of that of carbon vulnerable lands(CV-lands). To fulfill the gap after 2100 till the end of the third rotation, the average of temperature of the last ten years (2091-2100) is used. Temperature situation in simulation period is depicted in fig.S1.

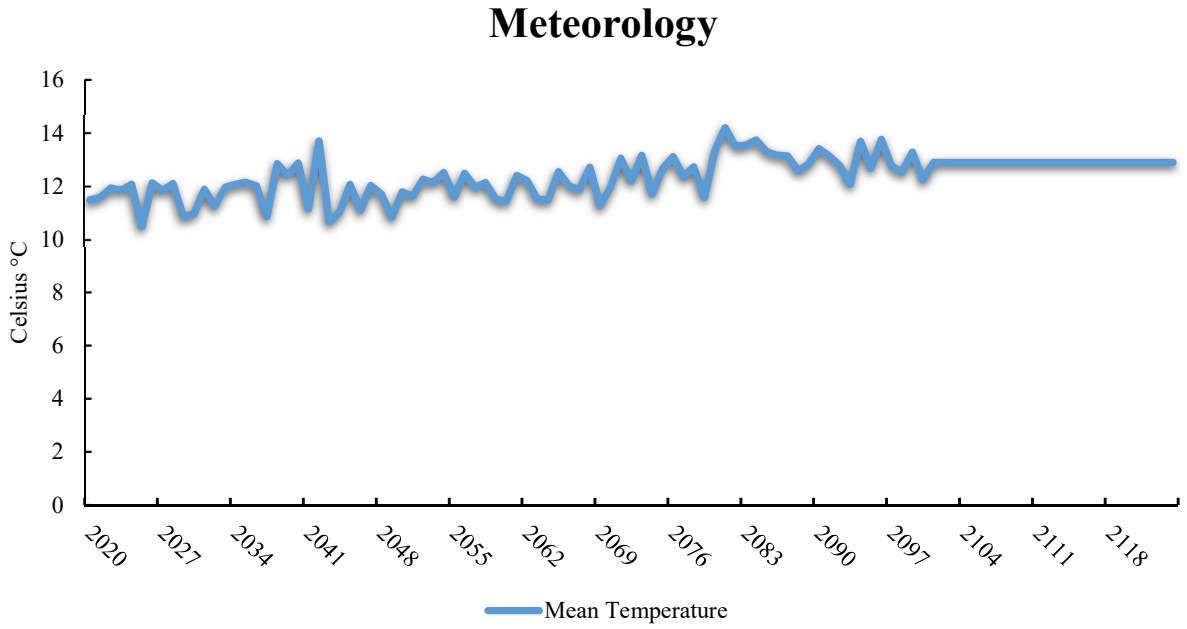


Fig. S1 Predicted temperature as inputs for C-Tool from 2022 to 2126.

Another important setting of C-Tool is the soil characteristics. Initial SOC stock and clay proportion are taken from the Harmonized World Soil Database(Nachtergaele et al., 2012) (FAO) according to the CV-lands range we defined before(Shen et al., 2022a), 42.35 t ha^{-1} and 0.0216 g kg^{-1} respectively. While C/N ratio is not included in the FAO database, 11 is used here as it is a general value for France(Dimassi et al., 2018; Launay et al., 2021).

Carbon inputs are calculated in two parts, belowground and aboveground. Aboveground carbon inputs include carbon from aerial biomass, woody dust and grated stump. What is called 'aerial biomass' is the set of foliage, seeds and pods, which are produced annually after the year 6 after cultivation(Nicolescu et al., 2018; Stone, 2009; Warne, 2016). Woody dust is the scrap left on-site during the cutting of trees(Santi et al., 2016). In other studies, stumps and roots were regarded as an integral for belowground(Albers et al., 2019), however, stump would be ground to prevent sprouting in our case(Malcolm et al., 2008), and left on the surface thus the crushed stumps were put as aboveground input, and the coarse root and fine root were the belowground input. Selective thinning and pruning are applied as a management to remove bad growing trees and to ensure the resources like sunshine for the healthy black locust(detailed in section 2.3). In one rotation, there are three cutting periods: first thinning, second thinning, and final logging, and pruning with the second thinning. Aerial biomass would fall down on the ground every year after the year 6, the quantity of aboveground and belowground biomass during the three cutting periods follow their corresponding growth rate (fig.6a, in the main paper). Aboveground and belowground carbon inputs are shown in table S2, with different dry mass and corresponding carbon percentage (table S1).

Table s2 shows the C input in C-tool for one rotation, and it is assumed to be the same for the other two rotations. In order to include in LCA the effect of residues decomposition after the cultivation period, simulations of SOC were performed for long term. For this simulation, in the year after cultivation (2126), all C input is 0. The results are represented in (fig. s2). In year 2177, the SOC stock is back to the level in 2022 (42.35 Mg ha^{-1}).

Table S1 Characteristics of different parts of black locust.

	Moisture%	Carbon%	Nitrogen%
Aboveground Woody biomass[a]	36.67%(González-García et al., 2011; Manzone, 2015)	48.17%(De Vries et al., 2014; "wood, black locust (Robinia pseudoacacia)," 1998)	0.57%("wood, black locust (Robinia pseudoacacia)," 1998)
Root[b]	36.67%(Rahmonov, 2009)	46.40%(Rahmonov, 2009)	2.19%(Rahmonov, 2009)
Aerial biomass[c]	6.13%(Bhat et al., 2014)	56.00%(Rahmonov, 2009; Rice et al., 2004)	2.13%(Rahmonov, 2009; Rice et al., 2004)

[a]: including branch, woody dust, stem, and stump.
[b]: including coarse root and fine root.
[c]: including foliage, pod, and seed.

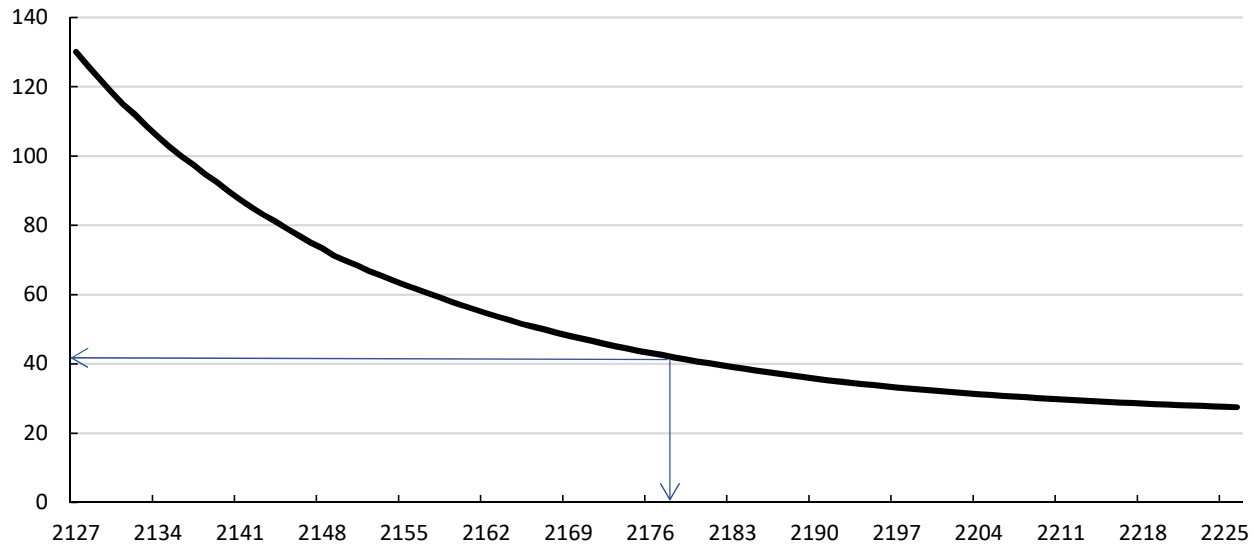


Fig. S2 SOC change in the CV-land after the cultivation period.

Table S2 Carbon input for C-Tool from one black locust cultivating rotation

Year	Aerial biomass residue[a]	Aboveground wood residue	Belowground
1	0.00	0.00	0.00
2	0.00	0.00	0.00
3	0.00	0.00	0.00
4	0.00	0.00	0.00
5	0.00	0.00	0.00
6	0.05	0.00	0.00
7	0.10	0.00	0.00
8	0.16	0.00	0.00
9	0.25	0.00	0.00
10[b]	0.84	0.48	4.65
11	0.25	0.00	0.00
12	0.33	0.00	0.00
13	0.43	0.00	0.00
14	0.54	0.00	0.00
15	0.67	0.00	0.00
16	0.81	0.00	0.00
17	0.96	0.00	0.00
18	1.13	0.00	0.00
19	1.31	0.00	0.00
20[c]	2.68	1.18	19.23
21	0.78	0.00	0.00
22	0.88	0.00	0.00
23	0.98	0.00	0.00
24	1.08	0.00	0.00
25	1.19	0.00	0.00
26	1.29	0.00	0.00
27	1.40	0.00	0.00
28	1.52	0.00	0.00
29	1.63	0.00	0.00
30	1.75	0.00	0.00
31	1.86	0.00	0.00
32	1.98	0.00	0.00
33	2.10	0.00	0.00
34	2.22	0.00	0.00
35[d]	2.34	3.30	65.24

[a]: foliage+seeds+pods.
[b]: first thinning.
[c]: second thinning +pruning;
[d]: harvesting.

2 Life cycle inventory

Inventories of black locust from cultivation till products disposal are presented here, all data are corresponding to the functional unit, which is 1 ha CV-land. To improve the data quality, inventory is built from multi sources, then choosing the average or median value. The main references are listed in the table.

2.1 Black locust cultivation

The principle for cultivating black locust on CV-lands (which are marginal lands) is avoiding agricultural managements unless they are necessary. Following this principle, fertilizer and irrigation are not applied because black locust tolerates dry and is a nitrogen-fix species(captures nitrogen and fix it in the soil) (Nicolescu et al., 2020; Seserman et al., 2018). Moreover, insecticide and herbicide are not needed either since black locust resists to fungal diseases, insect pests(Nicolescu et al., 2020; Seserman et al., 2018) and inhibits the growth of weed(Nicolescu et al., 2020). In this study, the main product is the cross laminated timber (CLT) from stem, thus selective thinning and pruning are necessary to promote valuable trees. Removing defective trees with narrow, full, and symmetrical crowns representing about one third of the height, could help produce high proportion of good quality roundwood.

The land is ploughed first, then black locust is cultivated with seedlings, with a density of 2240 seedlings ha^{-1}, considering the mortality and the defective trees (e.g. forked, badly shaped, wounded, or bent-over)(Keresztesi, 1983; Nicolescu et al., 2018). In fact, seedling planting and sprout are two common methods to cultivate black locust(Nicolescu et al., 2020, 2018). Black locust could sprout from stumps and roots, however, stumps would be crushed as mulch on the ground during logging, and after ploughing, roots are destroyed and then decomposed, thus seedling

plantingis adopted to cultivate the new generation here(Mazurek and Bejger, 2014). No fertilization, irrigation and pesticide is applied during the cultivation. First thinning is conducted at the year 10, with 50% of stems are cut(Keresztesi, 1983). After 10 years, 50% of forest would be thinned a second time, following a pruning of branches for the rest of the trees(Keresztesi, 1983; Rédei et al., 2012). Finally, all trees would be logged at the end of rotation, which is at the year 35 after seedling planting(Nicolescu et al., 2018). In addition, the cultivation of black locust occupies the CV-lands on which other plants grown initially, thus other products need to be induced to compensate this lack, leading to the indirect land use change (iLUC); the method of evaluating the iLUC is based on(Tonini et al., 2016), with the updated data used in a previous study(Shen et al., 2022a).

2.2 Black locust growth

Black locust is a long-live species, could live more than 90 years(Lovinska and Sytnyk, 2016), while the growth rate peaks at approximately 20 years of age(Nicolescu et al., 2018), the increment rate slows gradually till 35 years of age(Adamopoulos et al., 2005; Nicolescu et al., 2018; Vítková et al., 2017). Consider the initial target of planting black locust in the CV-lands is to have the maximum CO_2 sequestration, the optimal of rotation is 35 years in this study. After 35 years, black locust could be 22.23 m in height and 30 cm in diameter at breast height (DBH) (Adamopoulos and Voulgaridis, 2002; Keresztesi, 1983; Nicolescu et al., 2018). The growth rate of height and DBH of the stand tree was simulated as following:

$$H(t) = a * (1 - e^{-b*t})^c \quad (1)$$

$$DBH(t) = (p_1 + p_2 * t) * H(t)/100 \quad (2)$$

where H is the height at year t in meters; a, b, and c are empirical parameters equal to 25.5, 0.07, and 1.5214 respectively. DBH is in cm; $p_1$and p_2 are also empirical parameters equal to 85.9 and 1.4 respectively. To derive these, the known values of $H(35)$ (22 m; Adamopoulos and Voulgaridis, 2002; Nicolescu et al., 2018) and $DBH(35)$ (30 cm; Nicolescu et al., 2018; Vítková et al., 2017) were used. The values of both $p_1$and p_2 fit those that have been used in previous works (Nicolescu et al., 2018; Rédei et al., 2014, 2012).

To determine how much CO_2 would be captured every year and how much GHG would be emitted every year due to the plant growing and logging, especially the emission due to the selective thinning and logging, the growth of tree is modeled. Stem of tree is neither cone nor cylinder. Thus the volume of single stem is calculated as follows (Food and Agriculture Organization of the United Nations, 2005). The result is confirmed by other wood volume estimation equations(Rédei et al., 2014; Tabari and Salehi, 2008), and measurement results(Motta et al., 2009; Nicolescu et al., 2020).

$$V(t) = 0.42 * \pi(DBH(t)/2)^2 * H(t) \quad (3)$$

Where V (m^3) is the estimated volume of wood in the year t. The merchantable height is calculated as the height of the whole tree subtracted the height of stump, as stump is left on the ground. The height of stump ($Stpht$) is estimated by equation 2(Boston and Dysart, 2000):

$$Stpht(t) = 6.77 + 0.0355 * DBH(t) \quad (4)$$

$DBH(t)$ is the diameter at the breast height in the year 35, it should be noticed that the unit in this equation is inch, thus the unit should be converted. To expand the volume of the single tree to the biomass per hectare, the volume of the single tree multiplies the number of tree per

hectare, considering the wood density and moisture(Adamopoulos et al., 2007; Manzone, 2015). At the first, second and final logging, amount of black locust per hectare is 2240, 1120, and 560 respectively(Keresztesi, 1983; Motta et al., 2009). After that, the weight of branches and barks are added according to their weight ratio to the stem (25% and 5% respectively) (Laschi et al., 2016; Mirabella et al., 2014; Wilson and Sakimoto, 2005), it is assumed that all woody parts of the tree have the same moisture content(Vangeel et al., 2019).

As aforementioned in section 1, aerial biomass (foliage+pods+seeds) would fall down annually, since the year 6 till the end of the rotation. The moisture and composition differ slightly to the woody part(table S1), the emission from aerial biomass decomposition is accumulated from the year 6 till year 10, the year 11 till 20, and the year 21 till 35, corresponding to the inventory sheet of the first thinning, second thinning, and final logging respectively.

Following the approach described above, there are several assumptions listed for simulating the growth:

1) The whole tree is assumed to grow in the same rate;

2) The proportion of different parts are assumed to be the same during the whole rotation, like the shoot/root ratio. The only exception is branches, after pruning (at the year 20, after second thinning), 25% of branches are cut(Nicolescu et al., 2020).

3) For the harvested woody biomass(DM), 70% of weight is roundwood, 25% of weight is branch(Laschi et al., 2016), and 5% is bark(Wilson and Sakimoto, 2005), and 1.2% is aerial biomass (foliage+seeds+pods)(Addlestone et al., 1998).

4) The residues on the ground are assumed not to influence the existing black locust growing, both trees after thinning and planted for the next rotation;

5) Because sprouting is not considered in this study (reason is explained in the section 2.1), root would not sprout after thinning.

The results of height and diameter are shown in fig. s3. There are several different formulas to describe the height(Nicolescu et al., 2018; Rédei et al., 2014, 2012) and diameter(Nicolescu et al., 2018; Rédei et al., 2014, 2012) change of black locust every year, due to the different rotations and final biomass, the results are slight different, while the growth trends are similar.

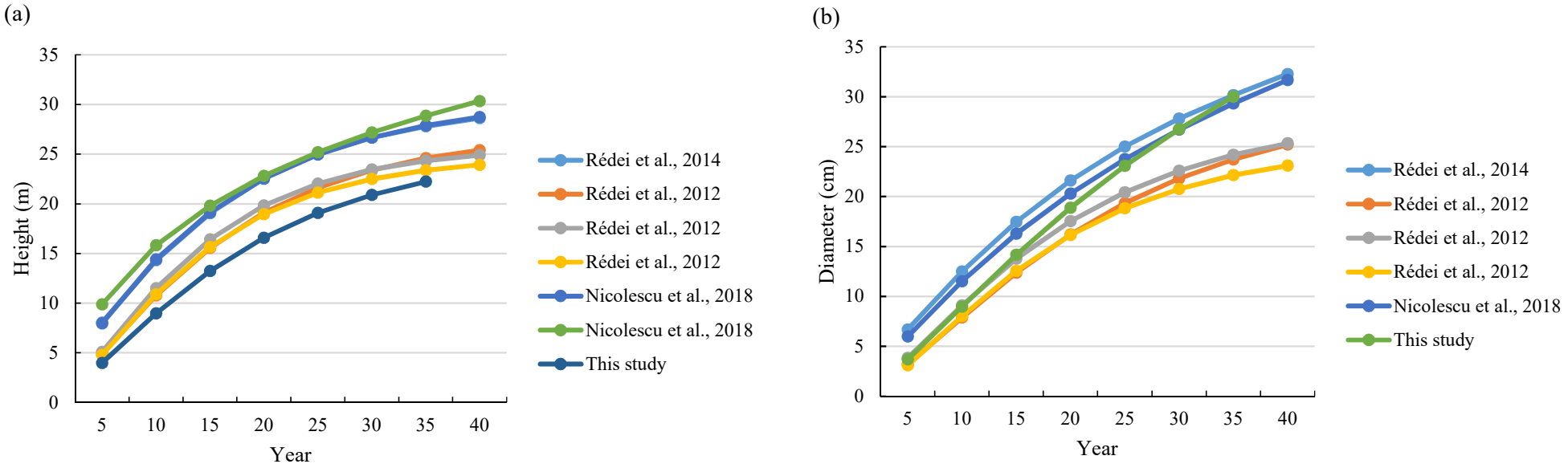


Fig. S3 Black locust growth trend in one rotation(a, height; b, diameter)

2.3 Logging

Black locust logging happens at the year of 10, 20, and 35 after seedling planting, for first thinning, second thinning, and final logging respectively, plus pruning is conducted right after the second thinning. The logging machine and loading process are included, data come from the ecoinvent(ecoinvent, 2020). Biomass from thinning and pruning is considered to be chipped as the ingredient for MDF, since they are not totally mature to be good quality wood. Black locust harvested from the final logging would be delimbed, branches are going to the chipper for MDF producing, and the stem is going to CLT manufacture. In all cases, bark would be incinerated(Silva et al., 2013), emission and avoided heat could be found in table S8. The wood harvesting produces 30 % of biomass loss which are left to decompose in forest, as aboveground carbon input (table S1&2), the rest loses in the air, regarded as PM 10 in the inventory(Wilson, 2010a). After cutting, stumps are left on the ground, would be crushed as mulch over the surface to prevent sprouting, because seedling planting is the only considered way to grow black locust in our case (table S7).

Table S3 Inventory sheet of black locust cultivation				
Cultivation				
Input	**Quantity**	**Unit**	**Source**	**Process**
Seedling	2240	p	(Nicolescu et al., 2018)	Tree seedling, for planting {GLO}| market for tree seedling | Conseq, U
Ploughing	1	ha	(Nicolescu et al., 2018)	Tillage, ploughing {GLO}| market for | Conseq, U
CO_2 total captured from air	1304.69	t		
Land occupation	350000	m2 a	1 rotation=35 years	Occupation, forest, extensive
iLUC	7.87	ha	(Shen et al., 2022a)	
Output				

Table S4 Inventory sheet of first thinning				
First thinning				
Input	**Quantity**	**Unit**	**Source**	**Process**
Harvested biomass	41.24	t		
Logging	2.70	hr	(ecoinvent, 2020)	Loader operation, large
	6.48	hr	(ecoinvent, 2020)	Skidding, skidder {RER}| skidding, skidder | Conseq, U
	6.89	hr	(ecoinvent, 2020)	Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | Conseq, U
Stump grinding	1.35	t		
Output				
Emission to air				
CO_2 from residue decomposition	19.95	t		
CH_4 from residue decomposition	0.24	t	(Ros et al., 2013)	
N_2O from residue decomposition	5.03	kg	(Nemecek and Kagi, 2007)	

Dust from logging	0.31	t	(Santi et al., 2016)	

Table S5 Inventory sheet of second thinning				
Second thinning				
Input	**Quantity**	**Unit**	**Source**	**Process**
Harvested biomass	173.00	t		
Logging	11.31	hr		Loader operation, large
	27.16	hr		Skidding, skidder {RER}| skidding, skidder | Conseq, U
	28.89	hr		Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | Conseq, U
Stump grinding	3.00	t		
Output				
Emission to air				
CO_2 from residue decomposition	99.18	t		
CH_4 from residue decomposition	1.13	t		
N_2O from residue decomposition	23.60	kg		
Dust from logging	1.29	t		
Table S6 Inventory sheet of final logging				
Final logging				
Input	**Quantity**	**Unit**	**Source**	**Process**
Harvested biomass	551.16	t		
Logging	36.05	hr	(ecoinvent, 2020)	Loader operation, large
	86.53	hr	(ecoinvent, 2020)	Skidding, skidder {RER}| skidding, skidder | Conseq, U
	92.04	hr	(ecoinvent, 2020)	Wood chipping, chipper, mobile, diesel, at forest road {GLO}| market for | Conseq, U
	46.19	hr	(ecoinvent, 2020)	Delimbing/sorting, excavator-based processor {RER}| delimbing, with excavator-based processor | Conseq, U
Stump grinding	7.56	t		
Output				
Emission to air				

CO_2 from residue decomposition	323.18	t		
CH_4 from residue decomposition	3.66	t		
N_2O from residue decomposition	77.01	kg		
Dust from logging	4.82	t		

Table S7 Inventory sheet of grinding stumps				
Grinding stumps				
Input	**Quantity**	**Unit**	**Source**	**Process**
Stumps (total from three cuttings)	11.91	t	(ecoinvent, 2020)	
Grinding	0.001	p	(ecoinvent, 2020)	Chipper, stationary, electric {GLO}| market for | Conseq, U
	377.55	kwh	(ecoinvent, 2020)	Electricity, medium voltage {CH}| market for | Conseq, U
	0.04	kg	(ecoinvent, 2020)	Lubricating oil {RER}| market for lubricating oil | Conseq, U
	0.08	kg	(ecoinvent, 2020)	Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U
Output				
Emissions from the decomposition of grated stumps are merged in table S4-6				

Table S8 Inventory sheet of bark incineration				
Bark incineration				
Input	**Quantity**	**Unit**	**Source**	**Process**
Bark (total from three cuttings)	37.68	t		
Incineration	1774.06	kwh	(ecoinvent, 2020)	Electricity, low voltage {FR}| market for | Conseq, U
	0.044	p	(ecoinvent, 2020)	Furnace, wood chips, with silo, 50kW {CH}| production | Conseq, U
Output				
Emission to air				
CO_2	30.50	t	(Nielsen et al., 2010)	
Sulphur dioxide (SO_2)	0.92	kg	(Nielsen et al., 2010)	
Nitrogen oxides (NO_X)	39.23	kg	(Nielsen et al., 2010)	
Non-methane volatile organic compounds (NMVOC)	2.47	kg	(Nielsen et al., 2010)	
Methane (CH_4)	1.50	kg	(Nielsen et al., 2010)	
Carbon monoxide (CO)	43.58	kg	(Nielsen et al., 2010)	
Nitrous oxide (N_2O)	387.41	g	(Nielsen et al., 2010)	
TSP	4.84	kg	(Nielsen et al., 2010)	
Cd	0.13	g	(Nielsen et al., 2010)	
Hg	0.19	g	(Nielsen et al., 2010)	
Zn	1.11	g	(Nielsen et al., 2010)	
PCDD/-F	6.78	µg	(Nielsen et al., 2010)	

PAH (BaP)	6.30	mg	(Nielsen et al., 2010)	
∑PAH	321.55	mg	(Nielsen et al., 2010)	
Naphthalene	1.12	g	(Nielsen et al., 2010)	
Ash	954.69	kg	(Nielsen et al., 2010)	
Marginal product				
Avoided heat	363282.94	MJ	(ecoinvent, 2020)	Heat, district or industrial, natural gas {FR}| heat and power co-generation, natural gas, conventional power plant, 100MW electrical | Conseq, U

2.4 CLT manufacture

After debranching and debarking, the roundwood is put on the land to dry in the open air, after several days, the moisture decreases to 15% after open-drying(Żelazna et al., 2019). The rough dried lumber with stickers are then trimmed before sawn into panel in certain size, residues produced during trimming are commonly sold as coproducts, herein would be collected and transported as the ingredients for MDF (section 2.5)(Bergman and Bowe, 2010). Trimmed lumbers are then sawn into the panel, several panels (commonly odd number, e.g. 3/5/7) are compressed together with a little resin according to different strength requirements(Dong et al., 2019). CLT could be used in lots in the construction field. Compare to the conventional construction material like brick, wall build by CLT need extra stone wool to reach the same thermal properties(Takano et al., 2014), which is 0.04 W m^{-1} K^{-1} and meets the standard of NF EN 15804 and NF EN 16783(Zieger et al., 2020). In the erection phase, building

woth CLT is much easier than with bricks, thus the energy consumption by using CLT is less, around 64 MJ/m^2 (100 mm thick). Also, 30% of time could be saved (which cannot be included in the inventory(Jayalath et al., 2020)). The lifespan of CLT is 50 years(Corradini et al., 2019).

Situation is similar for the demolition phase, while the energy consumption is 90% of that in the erection stage. What's more, during the demolition, there is a loss of 10% by mass(Jayalath et al., 2020), this loss is assumed to be collected and sent to the landfilling. Traditional LCA doesn't consider the carbon capture from air and carbon emitted as biogenic, however, we changed the characterization factor of both to track the carbon flow in this study (section 3). Half of the rest demolished CLT would be incinerated with heat recovery, while the other half is recycled (Guo et al., 2017). The common way to recycle CLT is to chop into wood chips (resin part is ignored since it's only 1% of the CLT, table s9). Herein, recycled CLT would go to the chipping process first, same as the harvested branches from the final logging (fig.1, main paper). Similar to recycled CLT, scraps from trimming and final sizing in CLT manufacture are assumed to be collected and then recycled as inputs for MDF manufacture. Because these scraps are already chips, the recycling would begin at the washing process (fig.1, main paper). The inventory for CLT manufacture and till disposal is shown below.

Table S9 Inventory CLT manufacture				
Open-dry				
Input	**Quantity**	**Unit**	**Source**	**Process**
Stem	368.50	t		
Open-dry	3158.05	m2a	(ecoinvent, 2020)	Occupation, industrial area
	1263.96	m2	(ecoinvent, 2020)	Transformation, from unknown
	1263.96	m2	(ecoinvent, 2020)	Transformation, to industrial area
Output				
Emission to air				
Water	92.85	t	(Corradini et al., 2019; Żelazna et al., 2019)	
Trimming				
Input	**Quantity**	**Unit**	**Source**	**Process**
Roundwood after drying	275.65	t		
Trimming	2914.23	kwh	(Corradini et al., 2019; ecoinvent, 2020)	Electricity, medium voltage {FR}| market for | Conseq, U
	0.00023	p	(ecoinvent, 2020)	Planing mill {RER}| production | Conseq, U
Output				
Scrap, collection an transporatation, DM	9.34	t		
Sawing				
Input	**Quantity**	**Unit**	**Source**	**Process**
Trimmed roundwood	264.62	t		
Electricity	4948.42	kwh	(ecoinvent, 2020)	Electricity, medium voltage {FR}| market for | Conseq, U
Diesel	6800.77	MJ	(ecoinvent, 2020)	Diesel, burned in building machine {GLO}| market for | Conseq, U
Lubricant oil	24.80	kg	(ecoinvent, 2020)	Lubricating oil {RER}| market for lubricating oil | Conseq, U

Output				
Scrap, collection an transporatation, DM	18.25	t		
Lubricant waste	3.71	kg		
Glue laminating& cutting/sanding				
Input	**Quantity**	**Unit**	**Source**	**Process**
Sawnwood	243.07	t		
Glue (UF)	2129.30	kg	(Chen et al., 2019; Wood Products Industry, 2002)	Urea formaldehyde resin {RER}| market for urea formaldehyde resin | Conseq, U
Electricity	22897.22	kwh	(ecoinvent, 2020)	Electricity, medium voltage {RER}| market group for | Conseq, U
Diesel	5955.22	MJ	(ecoinvent, 2020)	Diesel, burned in building machine {GLO}| market for | Conseq, U
Heat	393773.86	MJ	(ecoinvent, 2020)	Heat, central or small-scale, other than natural gas {CH}| heat production, hardwood chips from forest, at furnace 50kW | Conseq, U
Factory	0.0000059	p	(ecoinvent, 2020)	Wooden board factory, organic bonded boards {RER}| construction | Conseq, U
Output				
Formaldehyde	2.13	kg	(Basler et al., 2015; Wood Products Industry, 2002)	
Scrap, collection an transporatation, DM	41.16	t	(Bergman and Bowe, 2010)	
Marginal product				
Brick	259.5	t	(Takano et al., 2014)	Light clay brick {GLO}| market for | Conseq, U

Table S10 Inventory of the CLT use				
Erection				
Input	**Quantity**	**Unit**	**Source**	**Process**
CLT	196.59	t		
Nail	0.85	t	(Santi et al., 2016)	Metal working, average for aluminium product manufacturing {GLO}| market for | Conseq, U
Energy saved from construction	-160273.55	MJ	(Corradini et al., 2019; Guo et al., 2017)	Electricity, low voltage {FR}| market for | Conseq, U
Output				
Operation				
Input	**Quantity**	**Unit**	**Source**	**Process**
Extra insulation	28.05	t	(Takano et al., 2014)	Stone wool {GLO}| market for stone wool | Conseq, U
Output				

Table S11 Inventory of end of life of CLT.				
Demolition				
Input	**Quantity**	**Unit**	**Source**	**Process**
Energy saved from demolition	-144246.19	MJ	(Guo et al., 2017)	
Scrap, collection an transporatation, DM	16.64	t	(Jayalath et al., 2020)	
Output				
Disposal				
Input	**Quantity**	**Unit**	**Source**	**Process**
Biomass loss	16.64	t		
CLT going to the incineration	74.08	t		Waste wood, untreated {CH}| treatment of, municipal incineration with fly ash extraction | Conseq, U
	955.37	kg		Waste polyurethane {CH}| treatment of, municipal incineration with fly ash extraction | Conseq, U
Biomass going to the recycling	2538.8	tkm	(ecoinvent, 2020)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Conseq, U
Disposal of the extra insulation	28.05	t		Waste mineral wool {Europe without Switzerland}| market for waste mineral wool | Conseq, U
Disposal of nails	0.85	t		Scrap aluminium {Europe without Switzerland}| market for scrap aluminium | Conseq, U
Output				
Scrap collection& transporation, 1 t DM				
Input	**Quantity**	**Unit**	**Source**	**Process**
Collection	0.0349	kwh	(ecoinvent, 2020)	Electricity, medium voltage {FR}| market for | Conseq, U
Transportation	0.0287	tkm	(ecoinvent, 2020)	Transport, freight, lorry, unspecified {RER}| market for transport, freight, lorry, unspecified | Conseq, U

2.5 MDF manufacture

MDF is obtained from woody chips mixed with resin. There is no specific requirement for chips, thus lots of stuff could be used to make MDF. In this study, there are five main sources of woody chips, which are biomass from first and second thinning, branches from final logging, scraps from CLT manufacture, and recycled CLT. The logged biomass (including biomass from first thinning, second thinning, and final logging) and recycled CLT, need to be chopped into chips first, while scraps are considered as chips since they come from trimming and sizing. After chopping, chips need to be washed to remove dirt. Although chips from recycled CLT and scraps have went through the open-dry process, thus the moisture content is less than that of fresh logged biomass, after washing process, the moisture of chips from all sources is considered as the same. Clean chips would be refined by steam to soften the fiber. After that, the soften chips are mixed with resin and other additive, like $Al_2(SO_4)_3$ and paraffin, for improving the resistance to water and material strength, respectively. The resinated biomass need to be dried. The dried biomass is matted and compressed in a thermal process, and cut into desired size. Scraps during manufacture are not regarded as recyclable, but collected and treated as landfilling.

MDF is a widely used in construction, like wall or roof or furniture, herein we considered MDF would replace the PVC panel as ceiling materials(Onyeaju et al., 2012; Takano et al., 2014). After 12 years of use(Couret et al., 2017), MDF would be incinerated with heat recovery (ecoinvent, 2020), the lost mass because of demolition or transportation is considered as open-dump as the same in the CLT disposal (biomass loss), and carbon in the woody part is emitted as CH_4 and CO_2 (IPCC, 2019).

Table S12 Inventory of MDF manufacture				
Chipping				
Input	**Quantity**	**Unit**	**Source**	**Process**
Branches	135.94	t		
Demolished CLT	88.46	t		
Biomass from first thinning	38.74	t		
Biomass from second thinning& pruning	162.49	t		
Energy consumption	8695.17	MJ	(Kouchaki-Penchah et al., 2016)	Electricity, medium voltage {CH}| market for | Conseq, U
Lubricating oil	1.40	kg	(ecoinvent, 2020)	Lubricating oil {RER}| market for lubricating oil | Conseq, U
Machine	0.04	p	(ecoinvent, 2020)	Chipper, stationary, electric {GLO}| market for | Conseq, U
	2.80	kg	(ecoinvent, 2020)	Steel, low-alloyed, hot rolled {GLO}| market for | Conseq, U
Scrap, collection	8.37	t		Scrap, collection an transporatation, DM, to in assemble
Output				
Scraps	8.37	t		Waste wood, untreated {GLO}| treatment of waste wood, untreated, open dump, wet infiltration class (500mm) | Conseq, U
Washing				
Input	**Quantity**	**Unit**	**Source**	**Process**
Chipped biomass	417.27	t		
Chips from CLT manufacture	81.19	t		
Water for washing	298.22	m^3	(Rivela et al., 2007)	
Output				
Waste water	241.66	t	(Rivela et al., 2007)	Wastewater from medium density board production {RER}| treatment of wastewater from medium density fibreboard production, capacity 5E9l/year | Conseq, U

Steam refinery				
Input	**Quantity**	**Unit**	**Source**	**Process**
Washed branch	555.02	t		
Steam	872644.87	MJ	(Rivela et al., 2007)	Process steam from natural gas, heat plant, consumption mix, at plant, MJ FR S
Energy consumption	34015.12	MJ	(Kouchaki-Penchah et al., 2016)	Electricity, low voltage {FR}| market for | Conseq, U
Output				
Resinating				
Input	**Quantity**	**Unit**	**Source**	**Process**
Refined biomass	555.02	t		
Ureal formaldehyde resin	42.25	t	(Wilson, 2010a)	Urea formaldehyde resin {RER}| market for urea formaldehyde resin | Conseq, U
Paraffin	1.91	t	(Piekarski et al., 2017)	Paraffin {RER}| production | Conseq, U
Aluminium sulfate	0.38	t	(Wilson, 2010b)	Aluminium sulfate, without water, in 4.33% aluminium solution state {RoW}| production | Conseq, U
Energy consumption	12696.96	MJ	(Kouchaki-Penchah et al., 2016)	Electricity, low voltage {FR}| market for | Conseq, U
Output				
Waste resin	0.38	t		Hazardous waste, for incineration {Europe without Switzerland}| market for hazardous waste, for incineration | Conseq, U
Emission to air				
Formaldehyde	0.06	t		
Drying				
Input	**Quantity**	**Unit**	**Source**	**Process**
Resinated biomass	599.56	t		

Drying	20423.28	m^3	(Rivela et al., 2007)	Drying, natural gas {GLO}| market for | Conseq, U
Output				
Emission to air				
Water	157.17	t		
Methanol	8.40	kg		
Mat forming &thermal compression				
Input	**Quantity**	**Unit**	**Source**	**Process**
Biomass after drying	437.52	t		
Energy consumption, hot oil	418021.27	MJ	(Kouchaki-Penchah et al., 2016)	Heat, district or industrial, natural gas {Europe without Switzerland}| market for heat, district or industrial, natural gas | Conseq, U
Energy consumption, electricity	20601.90	MJ	(Rivela et al., 2006)	Electricity, low voltage {FR}| market for | Conseq, U
Output				
Sizing &sanding, input- Pressed mat				
Input	**Quantity**	**Unit**	**Source**	**Process**
Pressed mat	437.52	t		
Energy consumption, electricity	137159.81	MJ	(Rivela et al., 2006)	Electricity, low voltage {FR}| market for | Conseq, U
Scrap, collection an transportation, DM	1.96	t	(Kouchaki-Penchah et al., 2016)	
Output				
Marginal product				
PVC panel	849.34	t		Polyvinylchloride, bulk polymerised {GLO}| market for | Conseq, U

Table S13 Inventory of MDF disposal				
Chipping				
Input	**Quantity**	**Unit**	**Source**	**Process**
MDF	437.52	t		
Output				
Resin disposal	40.98	t		Waste polyurethane {CH}| treatment of, municipal incineration with fly ash extraction | Conseq, U
Woody part disposal, DM	335.85	t	(ecoinvent, 2020)	Waste wood, untreated {CH}| treatment of, municipal incineration with fly ash extraction | Conseq, U
	0.18	t	(ecoinvent, 2020)	Waste wood, untreated {GLO}| treatment of waste wood, untreated, open burning | Conseq, U
	3.21	t	(ecoinvent, 2020)	Waste wood, untreated {GLO}| treatment of waste wood, untreated, open dump, wet infiltration class (500mm) | Conseq, U

2.6 Carbon vulnerable lands

The cultivation of black locust would replace the original plants on carbon vulnerable lands (CV-lands). Thus, the influence of initial CV-lands is estimated to be a reference scenario to compare to the black locust. The time scale is the same as for the black locust scenario, namely 35 years. As previously stated (Shen et al., 2022), there are four land types identified as CV-lands: intensive grasslands, natural grasslands, rapeseed lands, and woody moorlands.

Intensive grasslands occupies 53% of CV-lands, the dominant plant is perennial ryegrass (*Lolium perenne* L.) (Kirwan et al., 2007; Plantureux et al., 2005). The cultivation of ryegrass and later silage process are considered here. The silage ryegrass is a kind of mixed feed, which could avoid a certain amount of palm, soybean, and maize as marginal products of oil, protein, and, carbohydrate respectively(Gomez-Campos et al., 2020) (method from Tonini et al., 2016).

In case of rapeseed (*Brassica napus* L.), after extracting rapeseed oil as the main product, the seed meal is sold as feed. The proportion of rapeseed in CV-lands is 20%.

For these two kinds of land covers, when they are replaced by black locust, more feeds (the marginal products that we calculated) need to be produced to fill their gaps in the market. These extra demands of marginal feeds would lead to more fertilization and land expansion for corresponding crops. This impact is considered as iLUC (table S3).

Heather (*Calluna vulgaris*) is the representative plant on both natural lands and woody moorlands (20% and 7% of CV-lands)(Inglada et al., 2017). Becauseno specific usage is known, all biomass grown on these two lands are assumed to decay on site. The inventory of CV-lands is built in table S14-18;

Furthermore, the SOC change on CV-lands is estimated by C-Tool, in the same time horizon (2021-2126) as the reference scenario. Soil characteristics and temperature inputs are the same as for black locust (all plants growth in the same conditions). Carbon inputs in C-tool are calculated according to the plant considered in simulation, including aboveground and belowground biomass every year (table S19). After estimating the SOC change for four land covers (fig.s5), an arithmetic mean of SOC is computed based on their proportions in the total area of CV-lands (0.53, 0.2, 0.2, 0.07 for intensive grasslands, rapeseed lands, natural grasslands, and woody moorlands respectivelym table S18), depicted in fig.6b in the main paper.

The biomass residues from the CV-lands with initial vegetation are decomposed totally after the lands conversion to black locust(Verchot et al., 2006), with the tillage applied to cleaning the field before the first black locust seedling planting.

Table S14 Inventory sheet of intensive grassland.

Silage				
Input	**Quantity**	**Unit**	**Source**	**Process**
Silage process[a, b]	8	t	(ecoinvent, 2020)	Ryegrass silage {CH}| catch crop growing, ryegrass, August-April, organic fertiliser 80 kg N, three cuts | Conseq, U; 8 t/ha is the amount of ryegrass that would go through the silage.

N fertilizer	222	kg	(Hamelin et al., 2012)	Nitrogen fertiliser, as N {GLO}| market for | Conseq, U
P fertilizer	53.47	kg	(Hamelin et al., 2012)	Phosphate fertiliser, as P2O5 {GLO}| market for | Conseq, U
K fertilizer	18.69	kg	(Hamelin et al., 2012)	Potassium sulfate, as K2O {GLO}| market for | Conseq, U
Lime	542.05	kg	(Hamelin et al., 2012)	Lime, packed {CH}| lime production, milled, packed | Conseq, U
CO_2 in air	12.32	t		CO_2 captured from harvestable part
CO_2 in air	12.58	t		CO_2 captured from above+ belowground residue
Output				
Ryegrass silage	20.6	t	(ecoinvent, 2020)	65% water content
iLUC	-1	ha	(COWI A/S and Utrecht University, 2019)	(Shen et al., 2022a)
Emission to air				
NH_3	69.92	kg	(Hamelin et al., 2012)	From urea
NH_3	4.97	kg	(Hamelin et al., 2012)	From mineral fertilizer like $(NH_4)_2HPO_4$ or $5Ca(NO_3)_2\ NH_4{\cdot}NO_3$
NO	7.64	kg	(Hamelin et al., 2012)	From fertilizer
NO	1.51	kg	(Hamelin et al., 2012)	From residue
NO_x	14	kg	(Hamelin et al., 2012)	
N_2	74.96	kg	(Hamelin et al., 2012)	
N_2O	4.31	kg	(Hamelin et al., 2012)	From fertilizer &residue

N_2O	1.58	kg	(Hamelin et al., 2012)	From N mineralized because of soil carbon loss
CO_2	11.28	t	(Hamelin et al., 2012)	From residue, considered the SOC increased.
CO_2	0.43	t	(Hamelin et al., 2012)	From urea
CO_2	1.23	t	(ecoinvent, 2020)	From carbon loss during the silage
NMVOC	0.36	kg	(Hamelin et al., 2012)	
Emission to water				
Nitrate	149.5	kg	(Hamelin et al., 2012)	N-leaching
Phosphorus	0.032	kg	(Hamelin et al., 2012)	P-leaching
Use of ryegrass silage				
Input	**Quantity**	**Unit**	**Source**	**Process**
Ryegrass silage	20.6	t		
Output				
CO_2, biogenic	11	t		All carbon in the silage would emit back to the atmosphere
Marginal products				
Carbohydrate	-2.4	t	(Tonini et al., 2016)	Maize grain {GLO}| market for | Conseq, U
Protein	-0.49	t	(Tonini et al., 2016)	Soybean meal {GLO}| market for | Conseq, U
Fats	-34.53	kg	(Tonini et al., 2016)	Palm oil, refined {GLO}| market for | Conseq, U

a: plant cultivation and land occupation are included in the process;
b: silage process is modified by using mineral fertilizer, consequential inputs and emissions are shown in the inventory;

Table S15 Inventory sheet of rapeseed.				
Input	**Quantity**	**Unit**	**Source**	**Process**
Oil extraction[a,b]	822	kg	(ecoinvent, 2020)	Rape oil, crude {Europe without Switzerland}| rape oil mill operation | Conseq, U
Output				
Crude rapeseed oil	822	kg	(ecoinvent, 2020)	
SOC change	1.18	t	(Clivot et al., 2019)	Carbon dioxide, to soil or biomass stock
iLUC	-1	ha	(COWI A/S and Utrecht University, 2019)	Indirect land use change (Shen et al., 2022a)
Marginal product				
Crude palm oil	822	kg	(ecoinvent, 2020)	Palm oil, crude {RoW}| palm oil mill operation | Conseq, U
Use of rapeseed				
Input	**Quantity**	**Unit**	**Source**	**Process**
Crude rapeseed oil	822	kg		
Output				
CO_2, biogenic	3814.93	kg		All C in rapeseed oil would emit back to the atmosphere.

a: plant cultivation and land occupation are included in the process;
b: the avoided protein because of the rapeseed meal is included in the process;

Table S16 Inventory sheet of natural grassland.				
Input	**Quantity**	**Unit**	**Source**	**Process**
CO_2 captured	3.72	t	(Vogtländer et al., 2014; Worrall and Clay, 2014)	
Land occupation	1	ha a	(ecoinvent, 2020)	Occupation, grassland, natural (non-use)
Output				
Emission to air				
N_2O	0.51	kg	(Pehme et al., 2017)	
NO_x	1.28	kg	(Pehme et al., 2017)	
NH_3	0.39	kg	(Pehme et al., 2017)	
NMVOC	3.8	kg	(European Environment Agency, 2019)	
CO_2	3.35	t	(Vogtländer et al., 2014; Worrall and Clay, 2014)	
Emission to water				
Nitrate	31	kg	(Decau et al., 2004; Hussain et al., 2019)	
Emission to soil				
SOC change	0.37	t	(Pehme et al., 2017)	Carbon dioxide, to soil or biomass stock

Table S17 Inventory sheet of woody moorland.				
Input	**Quantity**	**Unit**	**Source**	**Process**
CO_2 captured	3.72	t	(Vogtländer et al., 2014; Worrall and Clay, 2014)	
Land occupation	1	ha a	(ecoinvent, 2020)	Occupation, grassland, natural (non-use)
Output				
Emission to air				
N_2O	0.51	kg	(Pehme et al., 2017)	
NO_x	1.28	kg	(Pehme et al., 2017)	
NH_3	0.39	kg	(Pehme et al., 2017)	
NMVOC	19.33	kg	(European Environment Agency, 2019)	
CO_2	3.35	t	(Vogtländer et al., 2014; Worrall and Clay, 2014)	
Emission to water				
Nitrate	31	kg	(Hussain et al., 2019)	
Emission to soil				
SOC change	0.37	t	(Pehme et al., 2017)	Carbon dioxide, to soil or biomass stock

Table S18 C-vulnerable plantation[a].				
Input	**Quantity**	**Unit**	**Source**	**Process**
Marginal land left as marginal, intensive grasslands	-18.55	ha		
Marginal land left as marginal, rapeseed	-7	ha		
Marginal land left as marginal, natural grassland	-7	ha		
Marginal land left as marginal, woody moorlands	-2.45	ha		

[a]: to estimate the marginal lands for 35 years, we ran the CV-lands scenario 35 times in the SimPro, all processes only happen once is adjusted (e.g. land transformation).

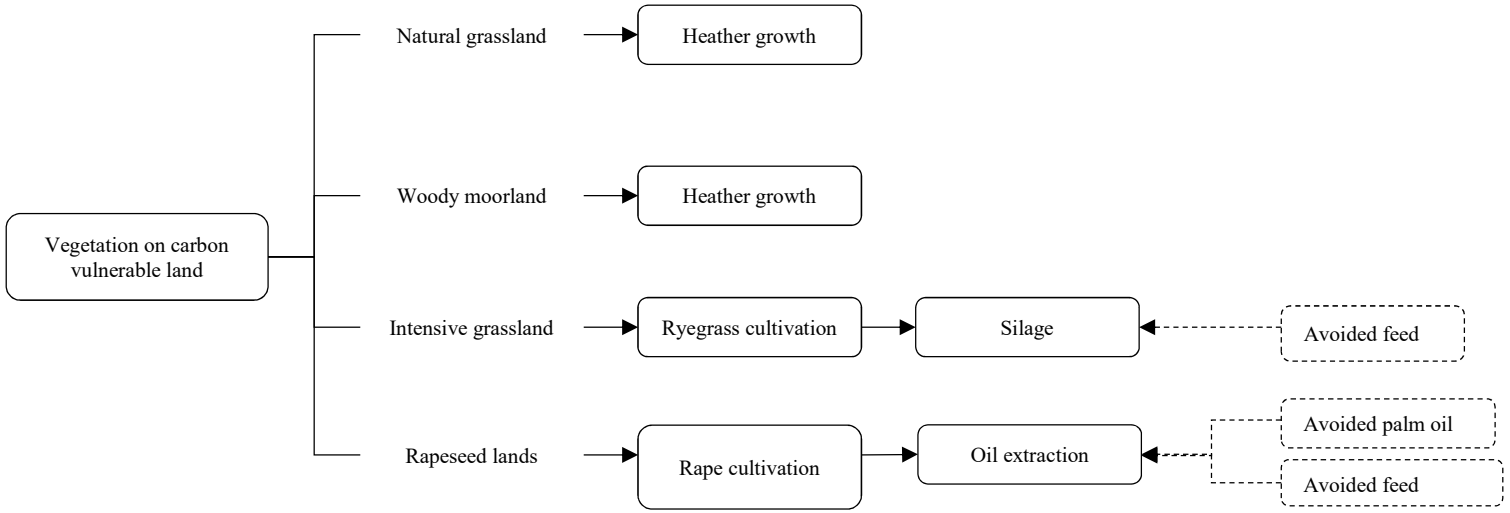


Fig. S4 Diagram of initial vegetation use

Annual C input of four types of the initial vegetation were shown in Table s19, which were assumed to be the same during the whole cultivation.

Table S19 Carbon inputs to C-tool.

	Aboveground carbon input Mg/ ha	Belowground carbon input Mg/ ha
Intensive grasslands	0.68	2.77
Rapeseed lands	3.12	1.17
Natural grasslands	1.07	0.0076
Woody moorlands	1.07	0.0076

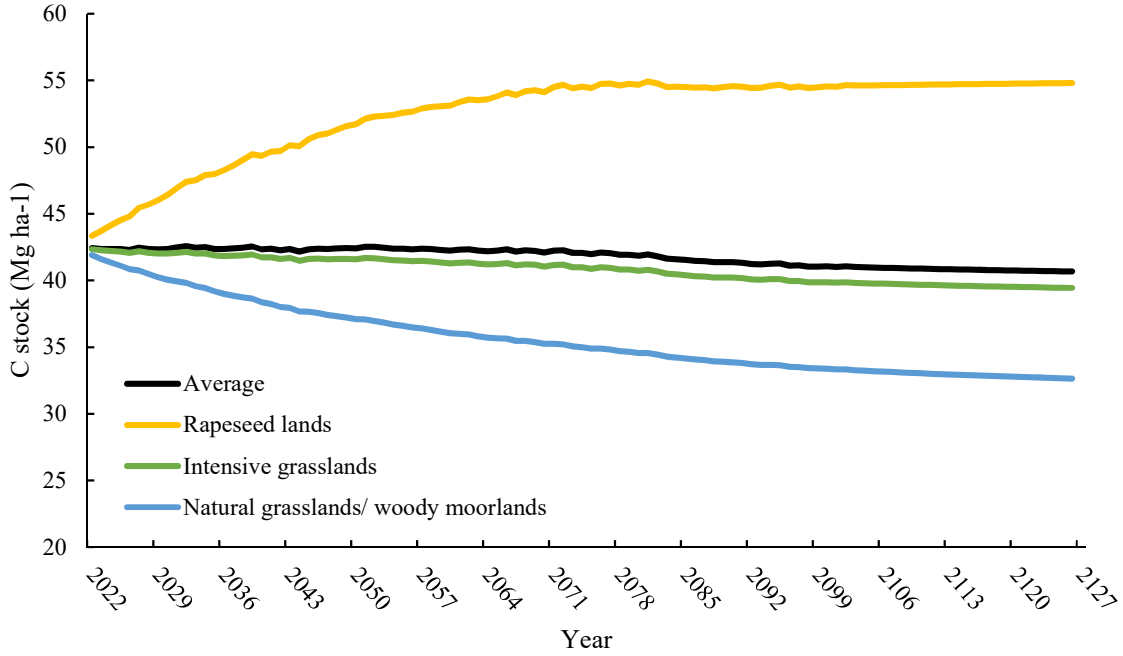


Fig. S5 The SOC simulation results for the four types of initial vegetation on CV-lands.

3 Consequential LCA

3.1 Environmental impact categories in consequential LCA

This study chose the Environmental Footprint initiative (EF) method, which is established and recommended by the European Commission (EC) to assess environmental impacts(Fazio et al., 2018). To track sources of different carbon flows and highlight the function of SOC but avoiding double counting, the EF method is slightly adapted as recommended by European Commission(Schau et al., 2013).

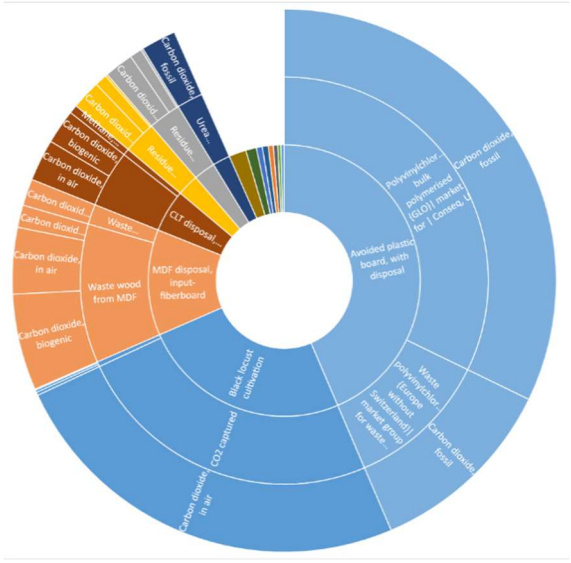
The characterization factors for CO_2 are : biogenic CO_2 =1 kg CO_2 eq, biogenic CO= 1.57 kg CO2 eq, biogenic methane= 34 kg CO_2 eq, CO_2 in air= -1 kg CO_2 eq, CO_2 stocked in soil or biomass= 0.

Under the EF scheme, 19 environmental impact categories are assessed, including three sub-impacts of climate change (fossile, biogenic and land transformation). European Commission gives three recommendation levels: satisfactory for categories in level I, needs some improvements for level II, and applied with caution for level III(Fazio et al., 2018).

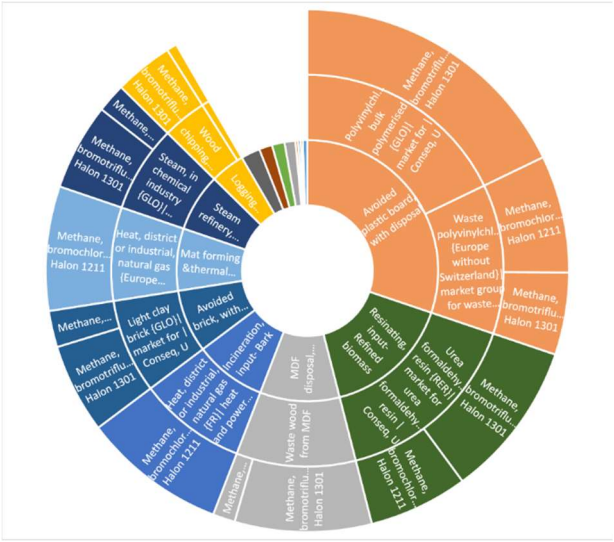
Table S20 Environmental impacts.

Impact category	Unit	Recommendation level
Climate change	kg CO2 eq	I
Ozone depletion	kg CFC11 eq	I
Ionising radiation, HH	kBq U-235 eq	II
Photochemical ozone formation, HH	kg NMVOC eq	II
Respiratory inorganics	disease inc.	I
Non-cancer human health effects	CTUh	III
Cancer human health effects	CTUh	III
Acidification terrestrial and freshwater	mol H+ eq	II
Eutrophication freshwater	kg P eq	II
Eutrophication marine	kg N eq	II
Eutrophication terrestrial	mol N eq	II
Ecotoxicity freshwater	CTUe	III
Land use	Pt	III
Water scarcity	m3 depriv.	III
Resource use, energy carriers	MJ	III
Resource use, mineral and metals	kg Sb eq	III
Climate change - fossil	kg CO2 eq	I
Climate change - biogenic	kg CO2 eq	I
Climate change - land use and transform	kg CO2 eq	I

3.2 Consequential LCA results : Contribution analysis

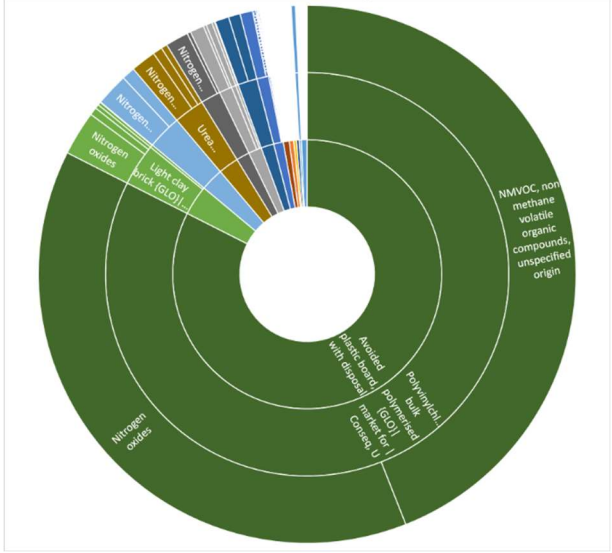


Climate change

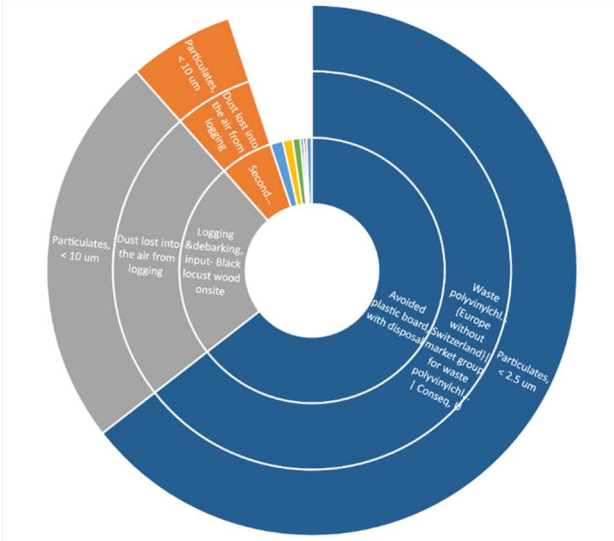


Ozone depletion

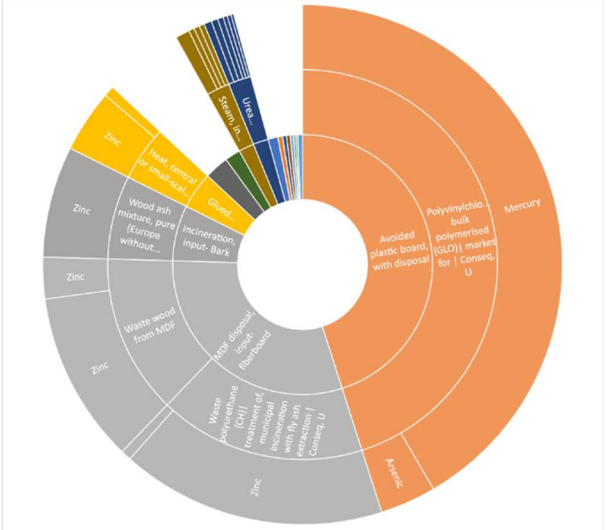
Ionizing radiation



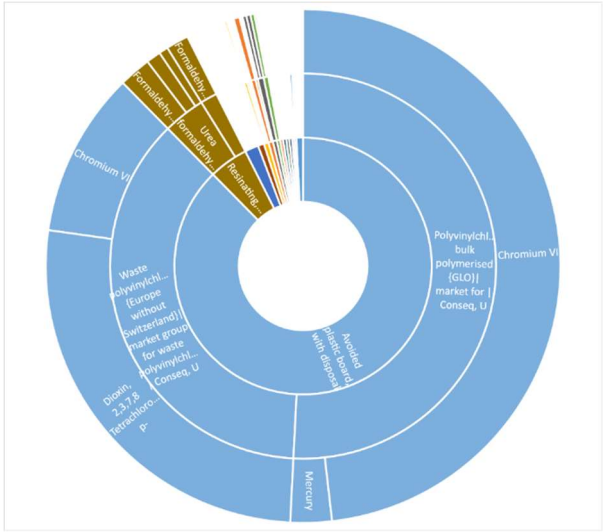
Photochemical ozone formation



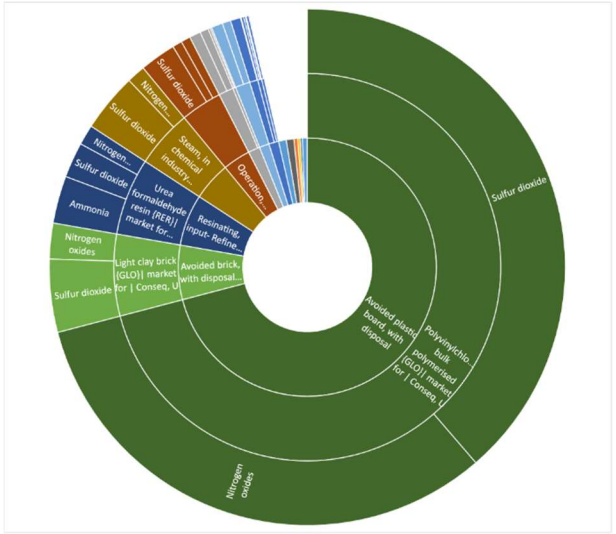
Respiratory inorganics



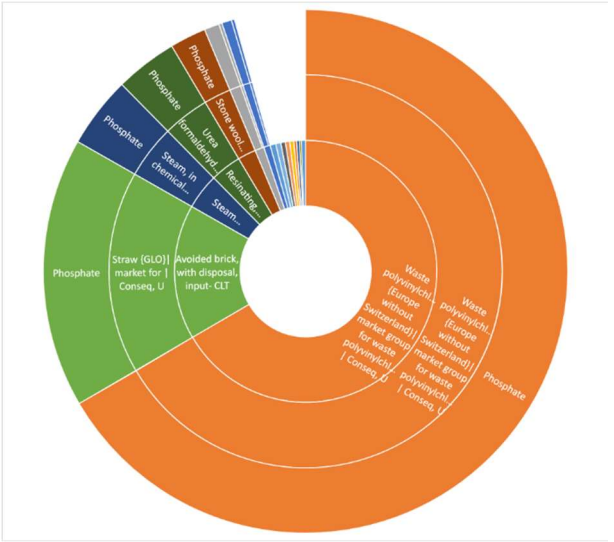
Non- cancer human health



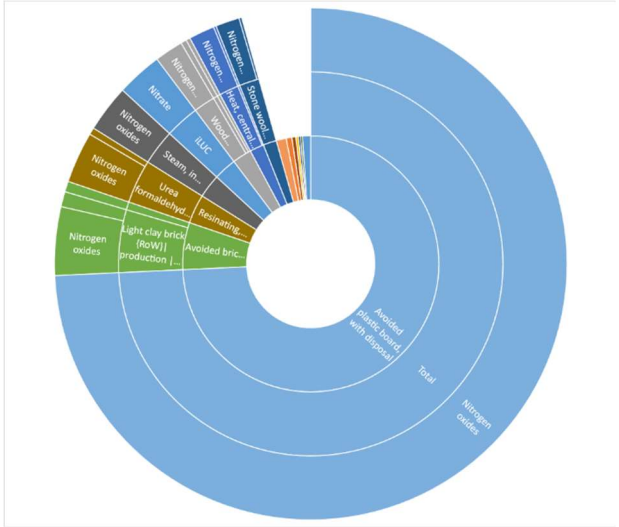
Cancer human health



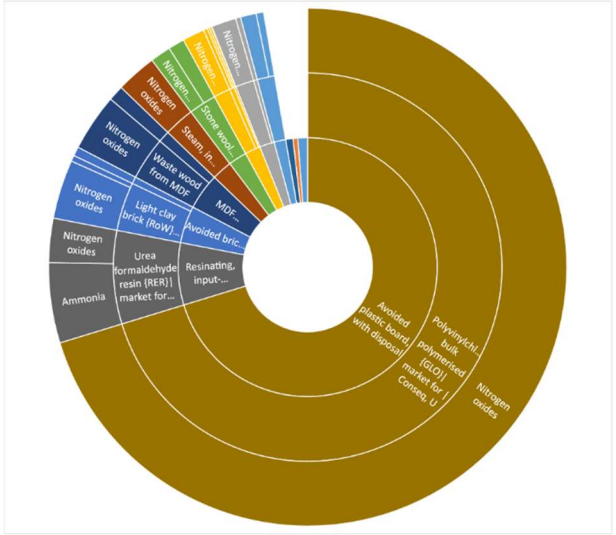
Acidification



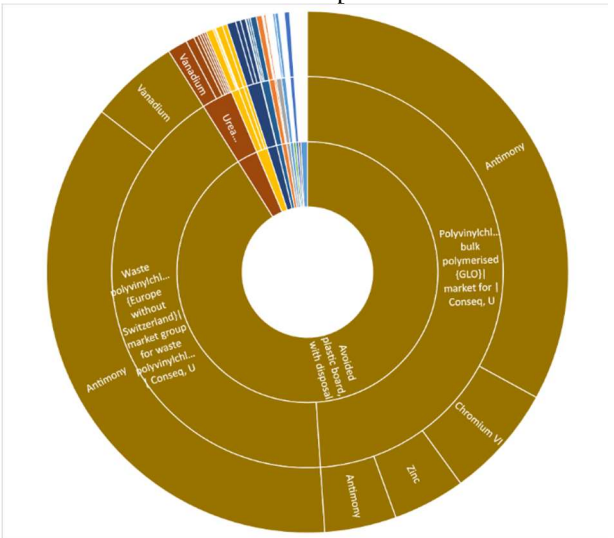
Freshwater eutrophication



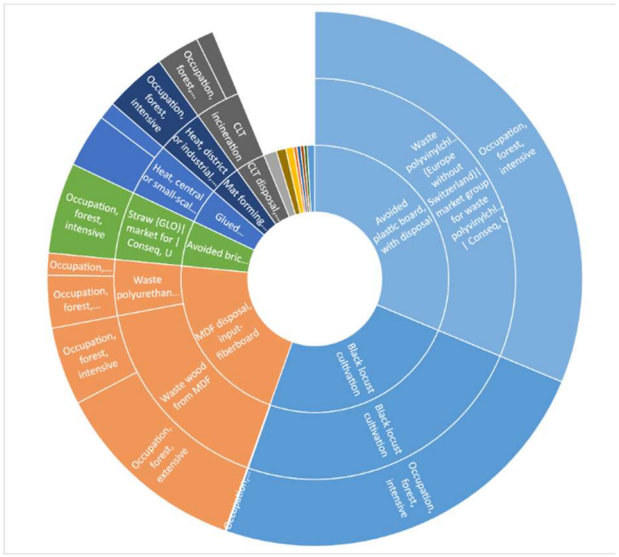
Marine eutrophication



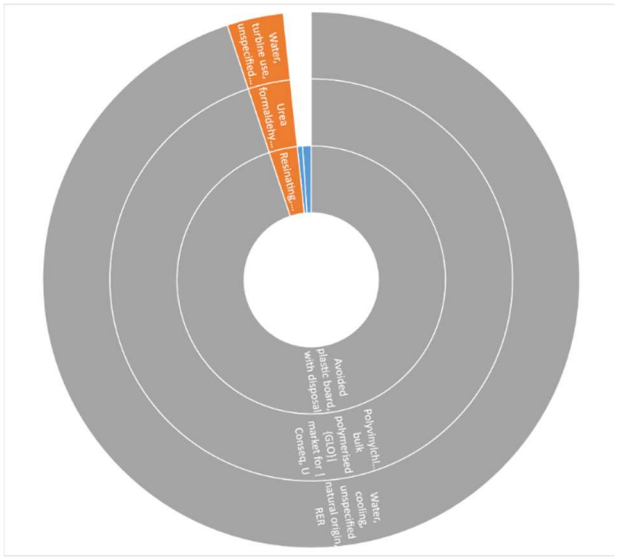
Terrestrial eutrophication



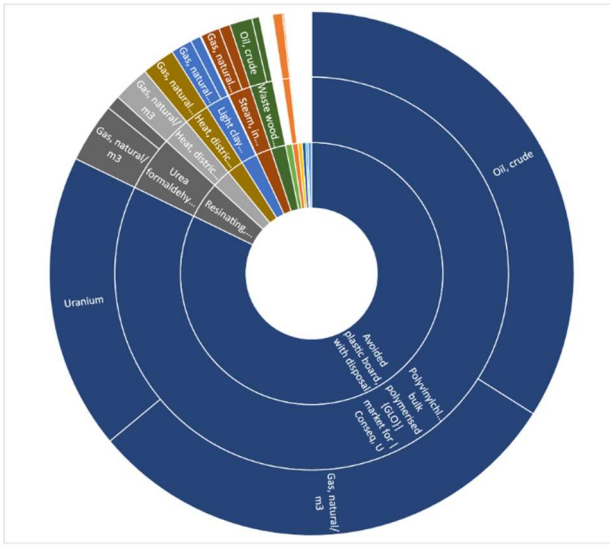
Ecotoxicity freshwater



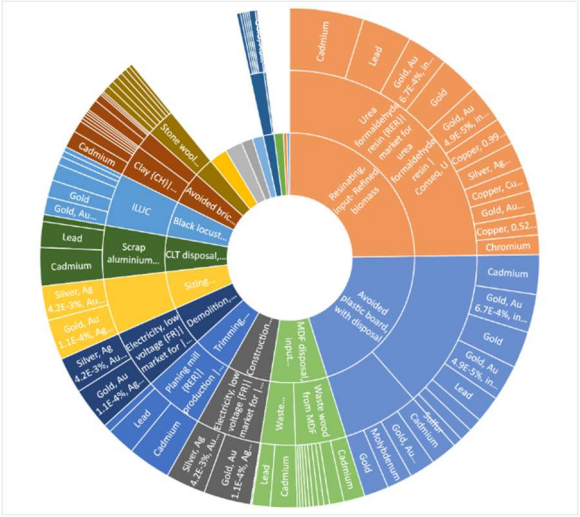
Land use



Water scarcity



Energy carrier, resource use



Mineral and mental, resource use

Fig. S6 Contribution analysis of LCA results of the scenario BL

4 Dynamic LCA

4.1 GHG considered in dynamic LCA

GHGs that are considered in dynamic LCA are listed in the table S21.

Table S21 GHG considered in dynamic LCA.

Black locust	CV-lands
Carbon dioxide	Carbon dioxide
Carbon dioxide, biogenic	Carbon dioxide, biogenic
Carbon dioxide, fossil	Carbon dioxide, fossil
Carbon dioxide, in air	Carbon dioxide, in air
Carbon dioxide, land transformation	Carbon dioxide, land transformation
Carbon dioxide, to soil or biomass stock	Carbon dioxide, to soil or biomass stock
Carbon monoxide	Carbon monoxide, biogenic
Carbon monoxide, biogenic	Carbon monoxide, fossil
Carbon monoxide, fossil	Carbon monoxide, land transformation
Carbon monoxide, land transformation	Chloroform
Chloroform	Dinitrogen monoxide
Dinitrogen monoxide	Ethane, 1,1-difluoro-, HFC-152a
Ethane, 1,1-difluoro-, HFC-152a	Ethane, 1,1,1-trichloro-, HCFC-140
Ethane, 1,1,1-trichloro-, HCFC-140	Ethane, 1,1,1,2-tetrafluoro-, HFC-134a
Ethane, 1,1,1,2-tetrafluoro-, HFC-134a	Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113
Ethane, 1,1,2-trichloro-1,2,2-trifluoro-, CFC-113	Ethane, 1,2-dichloro-
Ethane, 1,2-dichloro-	Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114

Ethane, 1,2-dichloro-1,1,2,2-tetrafluoro-, CFC-114	Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124
Ethane, 2-chloro-1,1,1,2-tetrafluoro-, HCFC-124	Ethane, hexafluoro-, HFC-116
Ethane, 2,2-dichloro-1,1,1-trifluoro-, HCFC-123	Methane
Ethane, hexafluoro-, HFC-116	Methane, biogenic
Methane	Methane, bromo-, Halon 1001
Methane, biogenic	Methane, bromochlorodifluoro-, Halon 1211
Methane, bromo-, Halon 1001	Methane, bromotrifluoro-, Halon 1301
Methane, bromochlorodifluoro-, Halon 1211	Methane, chlorodifluoro-, HCFC-22
Methane, bromotrifluoro-, Halon 1301	Methane, dichloro-, HCC-30
Methane, chlorodifluoro-, HCFC-22	Methane, dichlorodifluoro-, CFC-12
Methane, chlorotrifluoro-, CFC-13	Methane, dichlorofluoro-, HCFC-21
Methane, dichloro-, HCC-30	Methane, fossil
Methane, dichlorodifluoro-, CFC-12	Methane, land transformation
Methane, dichlorofluoro-, HCFC-21	Methane, monochloro-, R-40
Methane, fossil	Methane, tetrachloro-, CFC-10
Methane, land transformation	Methane, tetrafluoro-, CFC-14
Methane, monochloro-, R-40	Methane, trichlorofluoro-, CFC-11
Methane, tetrachloro-, CFC-10	Methane, trifluoro-, HFC-23
Methane, tetrafluoro-, CFC-14	Nitrogen fluoride
Methane, trichlorofluoro-, CFC-11	Sulfur hexafluoride
Methane, trifluoro-, HFC-23	
Nitrogen fluoride	
Sulfur hexafluoride	

4.2 Electricity and heat mix in the future

Table s22. Electricity mix in the future(Kassara et al., 2019)

Electricity, (TWh)	Gas	Other thermal	Nuclear	Photovoltaic	Onshore wind	Offshore wind	EnR(renewable energy)	Coal	Total
2020	0.6	13.2	422	18	33.5	0	79.5	12.7	579.5
	0.10%	2.28%	72.82%	3.11%	5.78%	0.00%	13.72%	2.19%	100.00%
2030	3.5	13.2	301.2	47	90	27	90	0	571.9
	0.61%	2.31%	52.67%	8.22%	15.74%	4.72%	15.74%	0.00%	100.00%
2040	8.7	6.6	215.5	69.2	149.5	27	116.2	0	592.7
	1.47%	1.11%	36.36%	11.68%	25.22%	4.56%	19.61%	0.00%	100.00%
2050	15.1	0	54.5	115.2	205.8	30.6	127.2	0	548.4
	2.75%	0.00%	9.94%	21.01%	37.53%	5.58%	23.19%	0.00%	100.00%

Table s23. Heat mix in the future(ADEME, 2018)

District heat, (Mtoe)	Others*	Fuelwood (cogeneration)	Fuelwood (heat only)	Gas (cogeneration)	Gas (heat only)	Geothermal	Coal and heating oil	Total
2030	1.3	1.3	1.1	1.2	2.1	0.4	0	7.4
	17.57%	17.57%	14.86%	16.22%	28.38%	5.41%	0.00%	100.00%
2035	1.2	2.1	0.8	1.2	2.1	0.8	0	8.2
	14.63%	25.61%	9.76%	14.63%	25.61%	9.76%	0.00%	100.00%
2040	1.2	2.8	0.5	0.8	1.5	1.1	0	7.9
	15.19%	35.44%	6.33%	10.13%	18.99%	13.92%	0.00%	100.00%
2045	1.2	3.5	0.3	0.4	0.7	1.5	0	7.6
	15.79%	46.05%	3.95%	5.26%	9.21%	19.74%	0.00%	100.00%
2050	1.1	4.2	0	0	0	2	0	7.3
	15.07%	57.53%	0.00%	0.00%	0.00%	27.40%	0.00%	100.00%

*: detailed in table s24.

Table s24. Heat mix of 'others' in the future(ADEME, 2018)

Methanisation	Household waste incineration	Residual heat	Solar thermal energy	Heat pumps
8.33%	50.00%	16.67%	16.67%	8.33%

4.3 Dynamic LCA results

For the whole life cycle of black locust scenario (105 years of cultivation), from biogenic sources, we obtain:

1) Total CO_2 absorption (negative in fig.s7): 3.91E+06 kg

2) Total CO_2 emission: 3.04E+06 kg

3) Total CO emission: 2.11E+02 kg

4) Total CH_4 emission: 1.92E+04 kg

5) Total N_2O emission: 3.08E+02 kg

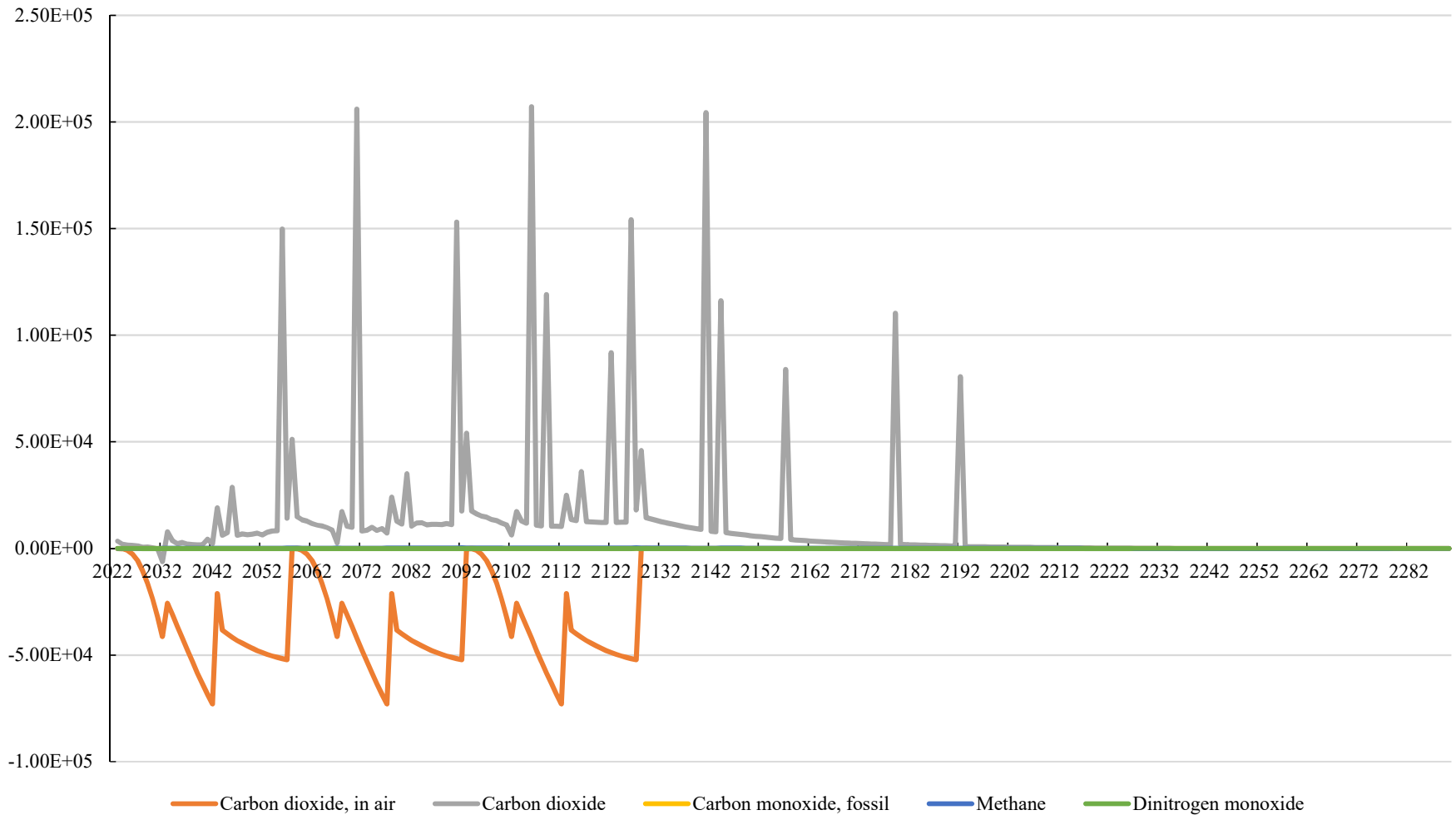


Fig. S7 Biogenic GHG flows (kg year^{-1}) for black locust scenario ('carbon dioxide in air' is the CO_2 captured, all other substances are emitted)

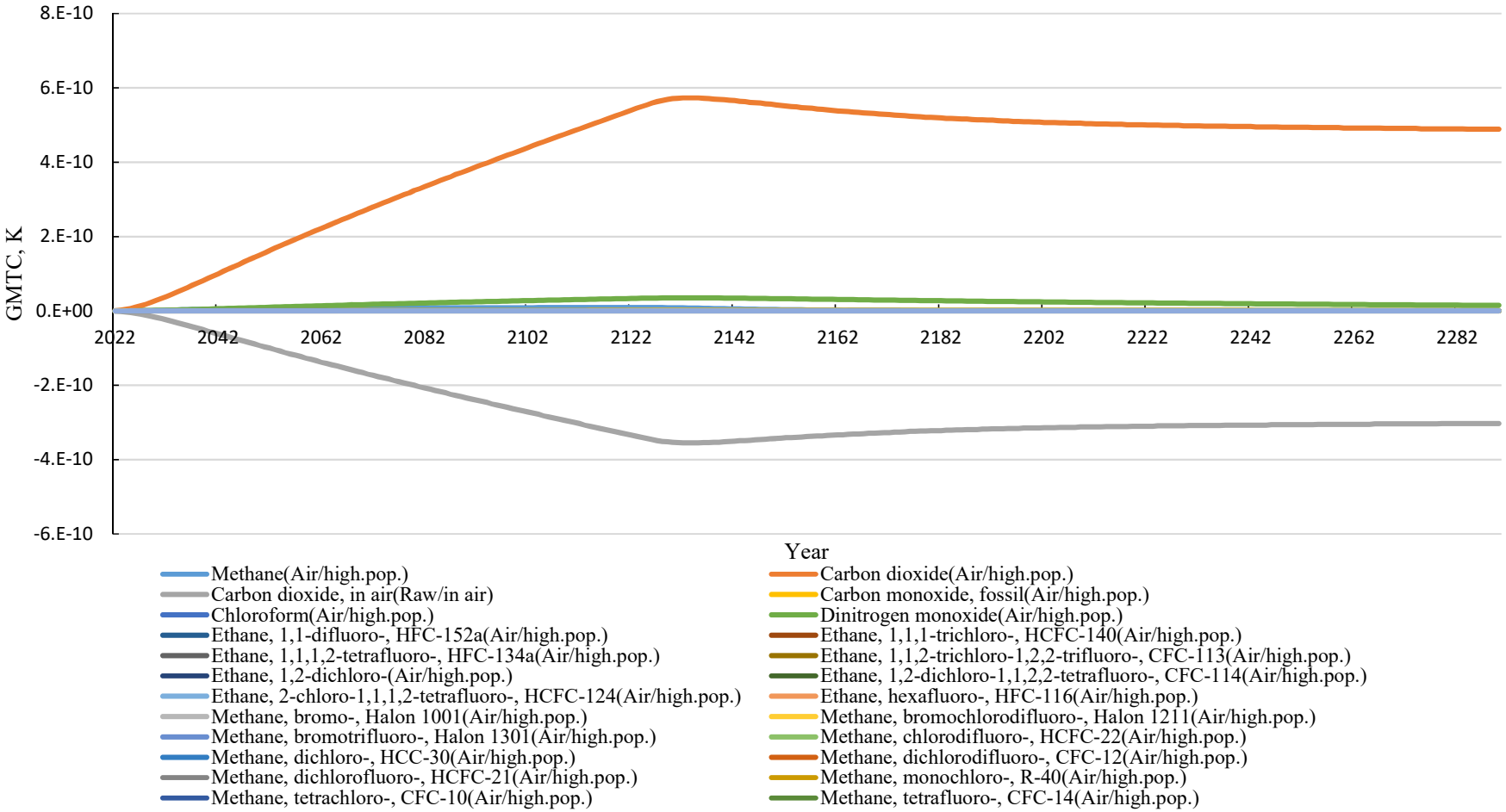


Fig. S8. GMTC of feed production and use in BLa scenario

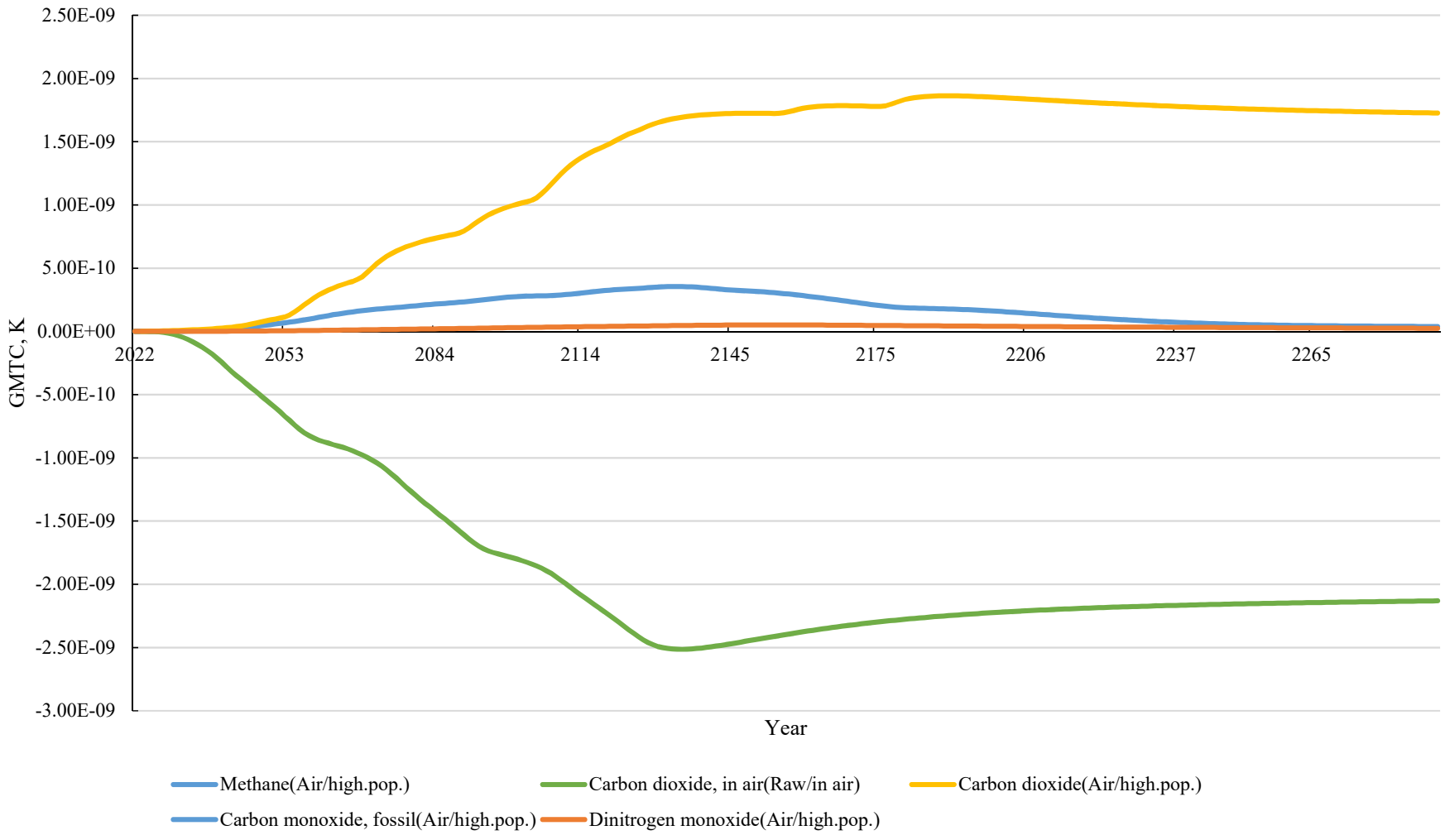


Fig. S9 GMTC of biogenic sources from black locust in BLa and BLc scenario

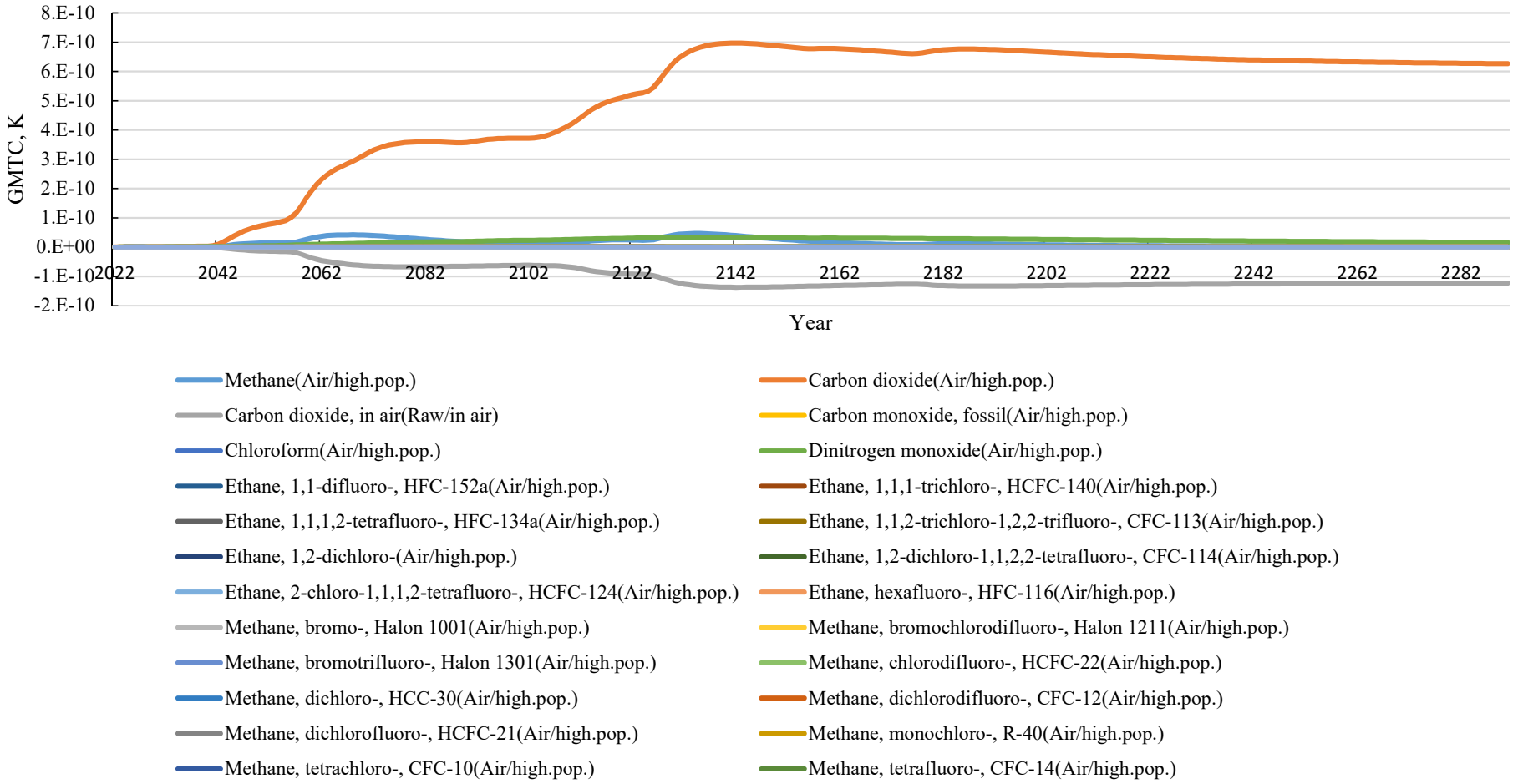


Fig. S10 GMTC of non-biogenic sources from black locust in BLa scenario

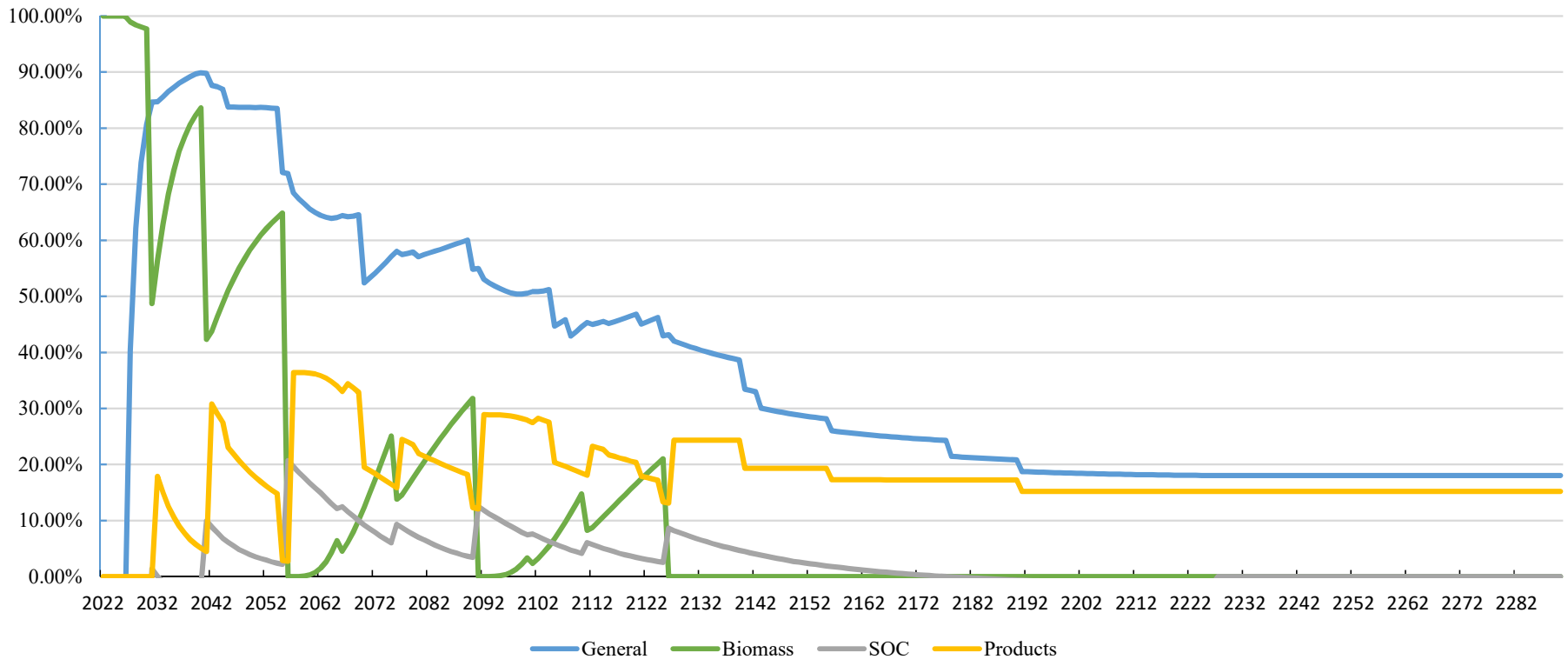


Fig. S11. C stock fraction in different components, with respect to the carbon absorbed (stock in the standing biomass, soil, products and total (general))

5 Sensitivity analysis

5.1 Method

In CLT disposal, the recycling rate is quite uncertain, and depends upon the country where it will be used (and disposed of). Since Europe is the largest current and future CLT consumer according to recent predictions, this study adopted a 45% recycling rate based on the European situation (Global Market Insights, 2021; Sahoo et al., 2019; Stora Enso, 2020). Yet, as this study covers a time period running until 2290, a higher recycling rate, e.g., 100%, is assumed as a sensitivity analysis (starting from the first year CLT recycling occurs, namely 2108). Similarly, light-clay bricks and polyvinyl-chloride boards have been considered as fixed displaced products of CLT and MDF. As a sensitivity analysis, concrete and plasterboard are considered as avoided products of CLT and MDF, respectively, on the basis of previous studies (Brander, 2017; Liu et al., 2016). For MDF, an additional variant was taken into account by considering petrochemical polypropylene (PP) as the replaced product.

5.2 Result

Since the production and disposal of plasterboards and PP boards are less impacting than PVC boards, replacing plasterboards and PP boards instead of PVC boards would bring less environmental benefits, resulting in a negative percentage in most impacts (Fig. 11, plasterboard, PP board), and mineral resources is the most sensitive impact among them. In climate change, replacing plasterboards is more sensitive than replacing PP boards, since the plasterboard production is the least GHG intensive (especially for fossil CO_2). Interestingly, for impacts that the scenario BLc was worse than scenario REFc, plasterboards and PP boards would lead to better results in land use and freshwater eutrophication.

At the end-of-life, the open burning of PP boards would emit a high amount of vanadium to soils, bringing more profits in ecotoxicity freshwater when it is avoided.

If CLT replaces concrete bricks rather than clay bricks, the ranking in most environmental impacts does not vary considerably except in ionizing radiation. Compared to clay bricks, concrete bricks demand less heat but more electricity. When CLT substitutes concrete bricks, this higher electricity consumption is avoided, leading to lesser C-14 and randon-222 emissions (from nuclear electricity).

When CLT is 100% recycled, more MDF are produced from recycled CLT, hence more plastic boards are avoided, this scenario performs better in most impacts, except in freshwater eutrophication (from avoided plastic board incineration) and mineral resources use (higher metal demand, e.g., cadmium and lead, for UF resin used in MDF manufacturing). Avoiding more plastic boards cannot compensate for this disadvantage. Among the four sensitivity scenarios, recycling 100% CLT could provide more benefits in most environmental impacts. Future studies could investigate the design of the recycling approach, the different approaches could cause more than double the difference in CO_2-eq (Cascione et al., 2022).

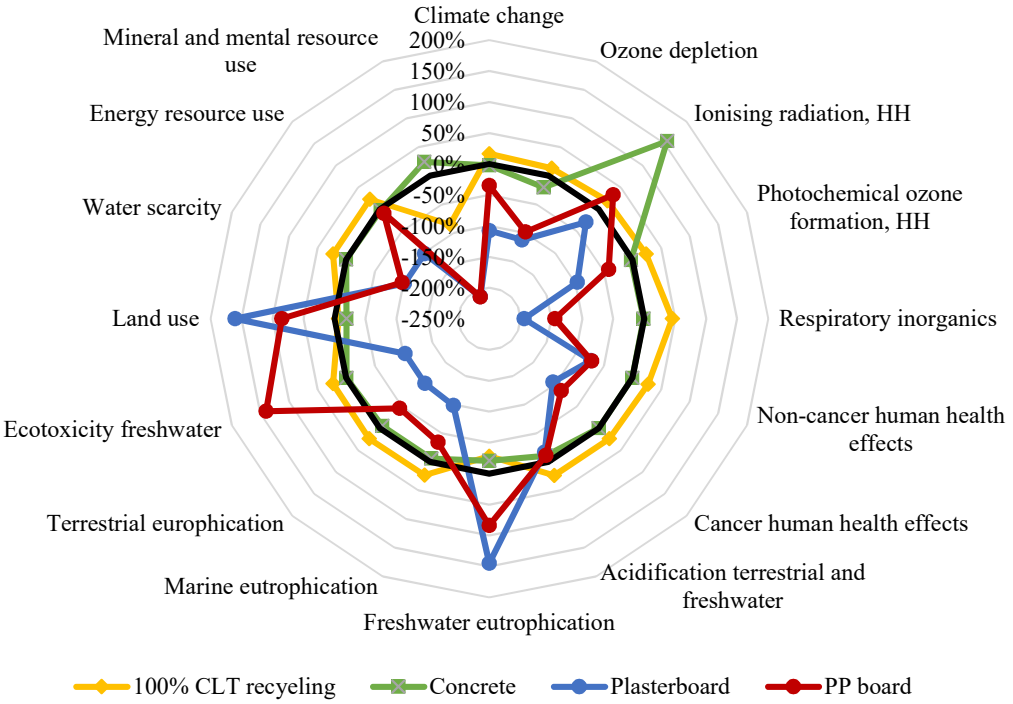


Fig. s12. Sensitivity analysis of: 100% CLT recycling, CLT avoids concrete, and MDF avoids plasterboard or PP board. The positive percentage means a scenario is better than the initial scenario in this impact.

6 Uncertainty analysis

6.1 Method

The uncertainty analysis was conducted according to the method proposed by Bisinella et al. (Bisinella et al., 2017, 2016). Accordingly, the parameters contributing the most to the impact results were identified in the contribution analysis. Then, a one-at-the-time perturbation analysis was performed to evaluate how 10% of each parameter's variation affects the impact of normalized results. The parameters have been assigned a probability distribution (triangular or normal), allowing, for each impact category, to calculate the uncertainty due to each parameter and the parameter's contribution to the overall uncertainty. Finally, a coefficient of variation is calculated, representing the overall uncertainty of a given impact. The stepwise application of this method is described as following.

The method called 'Global sensitivity analysis' is used in this study as it could reduce the calculation time significantly comparing to traditional Monte Carlo method, while getting similar results(Bisinella et al., 2016).

First, ten parameters are selected for the scenario BL as these parameters influence a lot the climate change impact according to the contribution analysis (fig. s6). Then, each parameter is increased by 10% in a one-at-a-time (OAT) manner while keeping all other parameters fixed at their value. A sensitivity coefficient (SC) is calculated as follow to represent the sensitivity of each parameter:

$$SC_i = \frac{\Delta score}{\Delta \text{parameter}} \quad (5)$$

With $\Delta score$ and Δparameter are differences before and after OAT of climate change score and parameter respectively, i=1,…n tested parameter. The SC_i calculated here is then used for calculating the analytical variance of the corresponding parameter (V_i):

$$V_i = {SC_i}^2 \cdot V_{input}(i) \tag{6}$$

Where $V_{input}(i)$ is the variance of each parameter, based on their uncertainty and distribution (table S25). The analytical variance of climate change category (V) in each scenario is the sum of V_i, and CV is used to indicate how uncertain the initial climate change score is.

$$V = \sum_{i=1}^{n} V_i \tag{7}$$

$$CV = \sqrt{V} / \, initial \; score \tag{8}$$

Parameters reaching 90% of the analytical variance (V) are selected to represent the uncertainty of climate change. In this way, the uncertainty of one impact is calculated; the same is applied to the other impacts.

6.2 Parameters in uncertainty analysis

The factors follow a normal distribution by default. If data for a certain factor are too few or do not follow normal distribution, but the potential mode is known, then triangular distribution is assumed(Lan et al., 2020). If we only have maximum and minimum value, then uniform distribution is assumed.

Table S25 Ten parameters considered for uncertainty analysis in the scenario BLc

	P1Quantity of avoided PVC	P2DM, yield	P3Non-CO2 GHG (CH4+N2O)	P4CH4:CO2 in landfilling	P5Recycling/ incineration in CLT disposal	P6UF resin amount	P7Nuclear/wind in electricity	P8Ash	P9Steam	P10Gas in the heat
μ	1.00	747.06	4936.91	19.18%	88.46	40.98	0.30	36.73	846423.01	31485.80
Unit	m	t	kg	%	t	t	%	t	MJ	m3
Uncertainty %	10%	10%	10%	10%	10%	10%	10%	10%	10%	10%
Δ	0.10	74.71	-493.69	0.02	8.85	4.10	0.03	3.67	84642.30	3148.58
Distribution	Triangle	Normal	Triangular	Triangular	Normal	Normal	Triangular	Triangular	Normal	Triangular
σ^2	5.56E-04	1395.2648	1.35E+04	2.04E-05	19.5629	4.1984	5.00E-05	0.7495	1791079764.5790	550753.0133

Table S26 Nine parameters considered for uncertainty analysis in the scenario REFc

	P1Area of intensive grassland	P2Area of rapeseed lands	P3Area of natural grasslands& woody moorlands	P4Amount of avoided palm oil (by rapeseed oil)	P5Amount of avoided feed (maize)	P6Amount of avoided feed (soybean)	P7Yield of ryegrass	P8Yield of rapeseed	P9N-fertilizer use in ryegrass cultivation
μ	18.55	7.00	9.45	6132.00	103.12	20.62	148.40	6132.00	5090.12
Unit	ha	ha	ha	kg	t	t	t	kg	kg
Uncertainty %	10%	10%	10%	10%	10%	10%	10%	10%	10%
Δ	1.86	0.70	0.95	613.20	10.31	2.06	14.84	613.20	509.01
Distribution	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Normal	Triangle
σ^2	0.8603	0.1225	0.2233	94003.5600	26.5863	1.0633	55.0564	94003.5600	14394.0676

6.3 Uncertainty analysis results- scenario BLc

The contribution analysis in section 3.2 identified ten parameters that play a key role in environmental impacts for the uncertainty analysis (table S25). The uncertainty results are presented in (table S27). The parameter column includes parameters representing the uncertainty in this impact, with corresponding uncertainty contributions. The values in the total column mean adding up these parameters together could represent the uncertainty in particular impact in which level (at least >90%). The coefficient of variance (COV) indicates how uncertain the impact result is. Six parameters are of significant contribution (P1, P2, P5, P6, P7, P10). It is concluded that climate mitigation from the plastic boards replacement is the largest negative score contributor in the static LCA. Consistent with this conclusion, most parameters are relative to the amount of avoided plastic boards (P1, P2, P5). In general, P2 represents the highest uncertainty in most impacts (13 of 16), since the yield of woody biomass influences the entire inventory, e.g. the amount of harvested woody materials would determine the amount of CLT and MDF products, further change the amount of avoided brick and plastic board and the disposal process. P6 links to the UF resin products, representing 73% of uncertainty in mineral resource use, because of the mental use in the production (e.g. cadmium, lead). The uncertainty of P7 is significant in respiratory inorganics only because of the high woody dust lost in the air during the logging.

6.4 Uncertainty in LCA results of the consequence that converting scenario REFc to scenario BLc

The contribution analysis and sensitivity analysis identified ten parameters in total that play key roles in environmental impacts (Table s26). Based on their representative of the uncertainty in all impacts, six of ten parameters are the most influential: quantity of avoided PVC; woody

biomass yield; recycling/incineration ratio in CLT disposal; used UF resin amount; dust emitted during logging; fossil fuel for avoided heat generation.

In general, the uncertainty of all impacts for BLc is lower than 10% except for mineral resource use (12%) (Table s27). Compared to BLc, the uncertainty of REFc is relatively higher, the freshwater eutrophication is the most uncertain impact (27%), due to the variance of the quantity of maize in the avoided feed (representative: 78%) (Table s28). Considering the ranges of impact scores could vary based on the analyzed results, the orders of the two scenarios observed in Fig. 7 and 8 could be confirmed since they are the same as in Table s29. There are significant differences between BLc and REFc in the sixteen environmental impacts, planting black locust on CV-lands is beneficial for thirteen environmental impacts.

Table S27 Uncertainty analysis results of the scenario BLc

Impact category	**Parameter**				**Total**	**COV**
Climate change	P1-50%	P2-28%	P3-21%		99%	±3.86%
Ozone depletion	P1-23%	P2-51%	P6-11%	P10-9%	94%	±7.11%
Ionizing radiation, HH	P2-72%	P5-5%	P6-17%		95%	±5.80%
Photochemical ozone formation, HH	P1-17%	P2-71%	P5-12%		100%	±5.98%
Respiratory inorganics	P1-27%	P2-30%	P5-19%	P7-24%	99%	±9.18%
Non-cancer human health effects	P1-13%	P2-72%	P5-13%		98%	±5.92%
Cancer human health effects	P1-18%	P2-70%	P5-12%		100%	±5.99%
Acidification terrestrial and freshwater	P1-20%	P2-68%	P5-10%		99%	±6.18%
Freshwater eutrophication	P1-17%	P2-66%	P5-16%		98%	±6.10%
Marine eutrophication	P1-19%	P2-70%	P5-11%		100%	±6.27%
Terrestrial eutrophication	P1-20%	P2-68%	P5-11%		100%	±6.22%
Ecotoxicity freshwater	P1-18%	P2-70%	P5-12%		100%	±5.97%
Land use	P1-76%	P5-14%			90%	±3.01%
Water scarcity	P1-17%	P2-71%	P5-12%		100%	±5.94%
Resource use, energy carriers	P1-18%	P2-71%	P5-11%		100%	±5.94%
Resource use, mineral and metals	P1-23%	P6-74%			97%	±12.41%

*P1: Quantity of avoided PVC; P2: woody biomass yield; P5: Recycling/incineration ratio in CLT disposal; P6: used UF resin amount; P7: Dust emitted during logging; P10: the CH_4 use in heat generation (the heat avoided by the heat generated from bark incineration), table S25
COV: coefficient of variation.

Table S28 Uncertainty analysis results of the scenario REFc

Impact category	**Parameter**						**Total**	**COV**
Climate change	P5-14%		P6-64%		P7-6%	P9-6%	90%	±15.35%
Ozone depletion	P1-9%	P3-9%	P5-28%	P7-33%		P9-12%	92%	±6.1%
Ionizing radiation, HH	P1-37%		P3-7%		P7-43%	P9-4%	90%	±7.23%
Photochemical ozone formation, HH	P1-25%		P5-13%		P6-9%	P7-46%	93%	±6.03%
Respiratory inorganics	P1-43%			P7-47%			90%	±7.08%
Non-cancer human health effects	P1-42%		P7-48%				92%	±6.84%
Cancer human health effects	P2-7%		P3-15%	P5-11%	P7-42%	P8-17%	92%	±4.71%
Acidification terrestrial and freshwater	P1-42%		P7-48%				90%	±6.87%
Freshwater eutrophication	P1-7%		P5-78%		P7-5%		90%	±27.33%
Marine eutrophication	P1-17%		P3-6%		P5-16%	P7-50%	90%	±5.15%
Terrestrial eutrophication	P1-42%		P7-48%				90%	±6.89%
Ecotoxicity freshwater	P1-33%		P6-26%		P7-32%		91%	±9.08%
Land use	P1-28%		P3-14%		P5-36	P6-16%	94%	±5.96%
Water scarcity	P1-30%		P5-35%		P7-29%		94%	±9.40%
Resource use, energy carriers	P5-67%		P6-5%		P7-6%	P9-13%	91%	±11.29%
Resource use, mineral and metals	P1-37%		P7-43%		P9-10%		91%	±7.12%

COV: coefficient of variation.

Table 29 Uncertainty range of LCA results[a].

Impact category		**Score range**			
		Scenario BLc		**Scenario REFc**	
	Unit	**Lower value**	**Higher value**	**Lower value**	**Higher value**
Climate change	t CO_2-eq	-2290	-2120	-58.9	-43.2
Ozone depletion	kg CFC11 eq	-0.0365	-0.0317	0.00459	0.00518
Ionizing radiation	kBq U-235 eq	9360	10500	1710	1980
Photochemical ozone formation, HH	kg NMVOC eq	-8710	-7730	449	507
Respiratory inorganics	disease inc.	-0.43	-0.358	0.0281	0.0324
Non-cancer human health effects	CTUh	-0.184	-0.163	0.242	0.278
Cancer human health effects	CTUh	-0.0517	-0.0459	0.0021	0.00231
Acidification terrestrial and freshwater	mol H+ eq	-4390	-3880	4300	4930
Freshwater eutrophication	kg P eq	382	432	-14.3	-8.14
Marine eutrophication	kg N eq	-1400	-1230	837	928
Terrestrial eutrophication	$x10^2$ mol N eq	-141	-124	199	229
Ecotoxicity freshwater	$x10^4$ CTUe	-399	-354	-109	-91.2
Land use	$x10^5$ Pt	261	277	147	165
Water scarcity	$x10^4$ m3 depriv.	-879	-780	-50.3	-41.7
Resource use, energy carriers	$x10^5$ MJ	-477	-423	2.34	2.93
Resource use, mineral and metals	kg Sb eq	0.217	0.278	1.39	1.60

[a] Impact with grey background means scenario REFc is better than BLc, otherwise, BLc is better.
Figures are presented with a maximum of 3 significant digits.

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