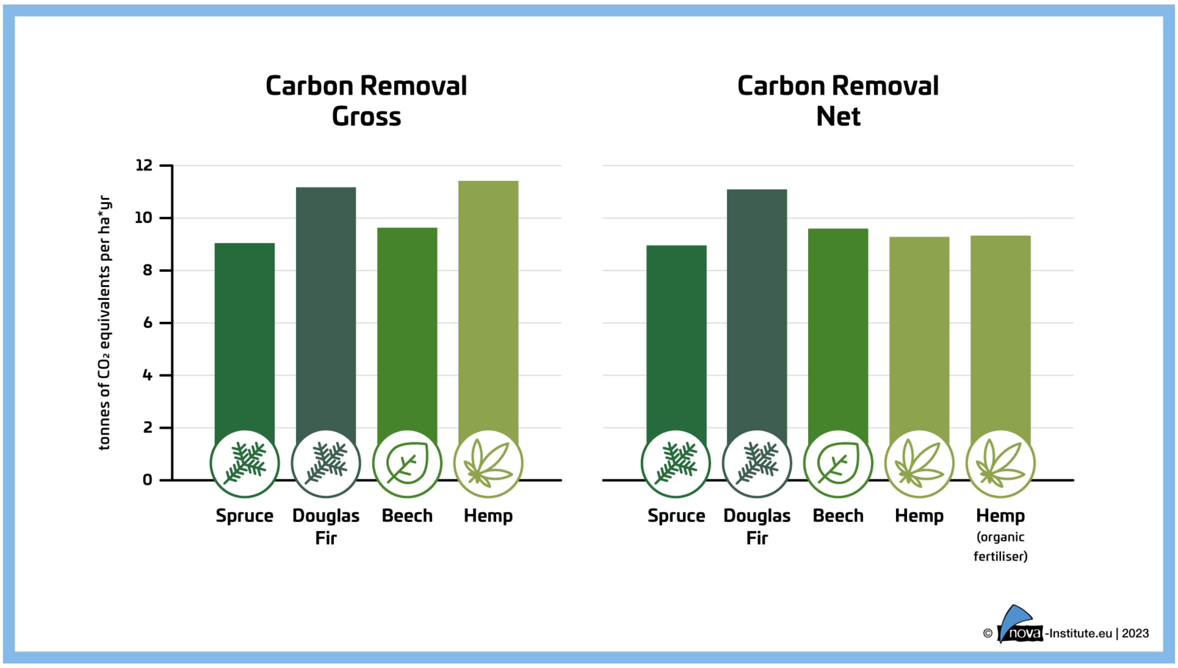
Carbon Storage in Hemp and Wood raw materials for Construction Materials

Final report, 06-2023

Niels de Beus, Matthias Stratmann, Michael Carus



submitted by

nova-Institut für politische und ökologische Innovation GmbH

Leyboldstraße 16
50354 Hürth
Germany

Tel. +49-175-7241616
Fax +49-2233-460 14 01
Email: niels.debeus@nova-institut.de

Table of Contents

List of figures

List of tables

1 Introduction

In recent years, climate change mitigation has been one of the top priorities in politics, which have set greenhouse gas emissions reduction targets across the board, including the construction industry. DG GROW reports that greenhouse gas emissions associated with the construction industry, including the extraction of raw materials and production of construction products, are estimated at 5-12% of the total national greenhouse gas emissions (DG GROW 2023). For example, the EU's circular economy action plan includes 'circular renovation' actions which aim at "minimising the footprint of buildings requires resource efficiency and circularity combined with turning parts of the construction sector into a carbon sink, for example through the promotion of green infrastructure and the use of organic building materials that can store carbon, such as sustainably-sourced wood". (EC 2020).

During photosynthesis, plants absorb CO_2 from the atmosphere and incorporate it in the biomass. The biomass can be used as raw materials for construction materials. When the biomass is used for the production of construction materials, the carbon in the biomass is (temporarily) stored in the product, for the lifespan of the product and possibly longer. As such, biomass can provide carbon, which regrows over time, to the industry. Basically, this process can move carbon from the atmospheric carbon pool, through photosynthesis to the biotic carbon pool and through processing further in the embedded carbon pool in materials (also called the technosphere). Nonetheless, there are also greenhouse gas emissions associated with this process.

As such, it is interesting to investigate the potential of biomass to store carbon in raw materials used in industry, more specifically the construction industry. What is the potential of biomass to supply the construction industry with raw materials containing temporarily stored biogenic carbon per hectare and year? Are there differences between various biomass types? What is the associated reduction of atmospheric greenhouse gasses due to the carbon in the raw materials? What are the emissions of greenhouse gasses associated with this provision of raw materials? This study will look into these questions for wood and hemp based raw materials which can be used in the construction industry. The production of the construction materials, and the associated emissions with the conversion of the raw materials to final products, is outside the scope of this assessment due to the wide variety of construction materials which can be produced from the raw materials.

To avoid confusion in terminology, it is important to note that the stored biogenic carbon in construction materials/products is the result of photosynthesis which has removed carbon dioxide from the atmosphere. The stored carbon is expressed in CO_2eq. based on the carbon content of the raw material. The removal of CO_2 from the atmosphere during photosynthesis is a greenhouse gas removal. Furthermore, this stored carbon can be released in the form of greenhouse gases at the end-of-life of the product. This is not included in this study, nor is the effect of temporal carbon storage in products.

Finally, it is important to note that this study aims to investigate the potential of wood and hemp to supply the construction industry with raw materials containing carbon, and the emissions associated with the provision of these raw materials. Conclusions regarding superiority of one biomass source over another are not intended to be drawn from this study, as this depends on many variables, which are not all covered by this study. For example, the functionality of the construction materials, additional processing required to manufacture construction materials but also the local conditions for biomass production. This study aims to show the potential of hemp and wood to provide raw materials containing carbon to the construction industry, to investigate the potential of bio-based construction materials to contribute to a more sustainable construction industry.

A list of potential construction materials made from hemp and wood raw materials is provided on the right side of Figure 1.

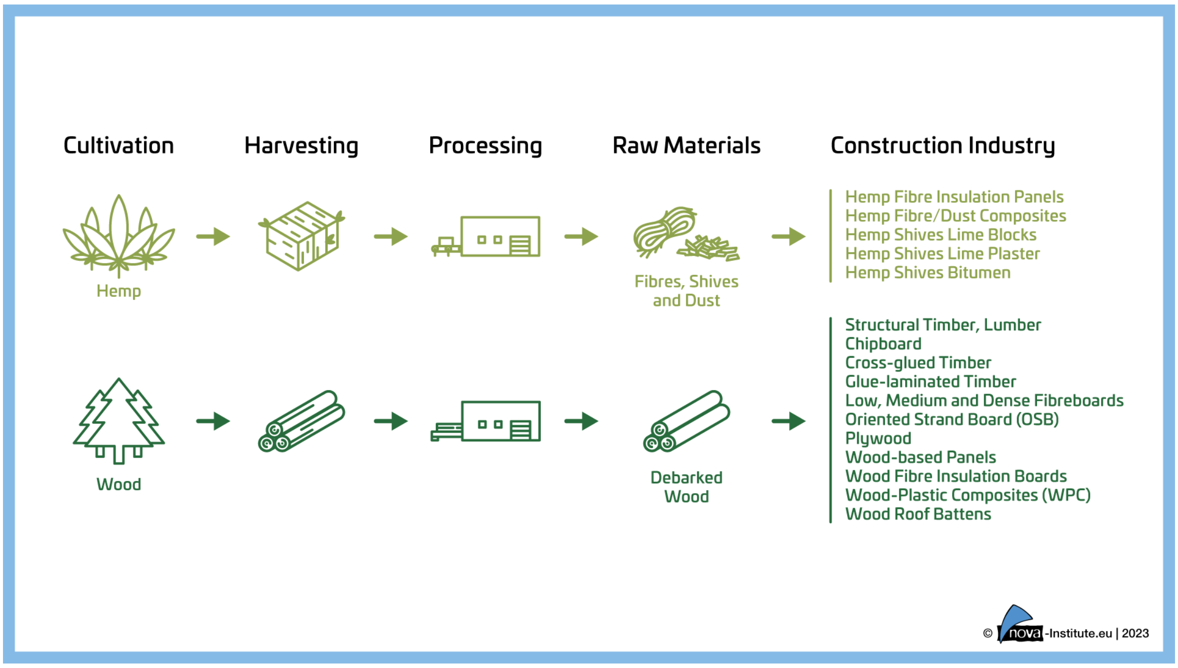


Figure 1. Schematic overview of the value chains for the provision of raw materials from wood and hemp.

1.1 Carbon Removal Certification

The storage of CO_2 in building products is an interesting option within the proposed framework of the "Carbon Removal Certification" in the European Union.

The EU certification of carbon removals is currently being developed in two steps: first, high-level quality criteria will be developed, followed by a second step in which detailed certification rules for the measurement, monitoring, reporting and verification of carbon removals from both industrial and nature-based activities will be developed. The Environment Council held a first policy debate on the file on 16 March 2023. In the latest available proposal (EC 2022), the aim of the EU carbon removal certification framework is to scale up carbon removal activities and fight greenwashing by empowering business to show their action in this field. The proposal sets out a voluntary EU-wide framework to certify carbon removals generated in Europe. It sets out criteria to define high-quality carbon removals and the process to monitor, report and verify the authenticity of these removals. To receive certification, the carbon removals will need to be correctly quantified, deliver additional climate benefits, strive to store carbon for a long time, prevent carbon leaks, and contribute to sustainability. These four criteria are called the QU.A.L.ITY criteria (Quantification, Additionality and baselines, Long-term storage and sustainability).The proposal also sets out requirements for third party verification and certification of carbon removals, in order to harmonise the certification process, ensure environmental integrity and build public trust. (EC 2022)

Of particular importance is which processes or products are eligible for the Carbon Removal Certificate in principle. Currently, the proposal sets out three ways to remove and store carbon, which can be certified which includes: (EC 2022):

- Nature-based solutions, such as restoring forests, soils, and innovative farming practices;
- Technology, such as bioenergy with carbon capture and storage, or direct air carbon capture and storage;
- Long-lasting products and materials, such as wood-based construction.

It should be noted that the proposal does not define "long-lasting", though the "carbon removal" and "carbon removal activity" definitions include the possibility to store biogenic carbon in such products and materials. Against this background, the present study takes on a special significance, as the carbon storage effects of hemp raw materials, to be used for long-lasting products (construction industry) is investigated. The results could therefore have an influence on the acceptance of bio-based construction materials under the carbon removal certification framework.

The European Commissions' DG Agri reports on the hemp production, uses and regulations related to hemp. It reports the cultivation area of hemp in the EU, 32,000 ha in 2021, and a number of environmental benefits associated with hemp cultivation including "Carbon storage: one hectare of hemp sequesters 9 to 15 tonnes of CO_2, similar to the amount sequestered by a young forest, but it only takes five months to grow." Furthermore, it reports on the use of hemp fibres in the construction industry, where three main products are mentioned; lime hemp concrete, hemp wool and fibre-board insulation. (DG Agri 2022)

From the text above, it can be seen that the EC is aware of the potential environmental benefits of the use of hemp and that it seems to fit with the requirements defined in the proposed carbon removal certificate framework.

This study will provide insight in the carbon removal potential of hemp and wood raw materials for long-lasting products and materials, including GHG emissions associated with the provision of the raw materials.

2 Goal and scope

The goal of this study is to quantify the amount of carbon stored (in CO_2eq.) in raw materials usable in construction provided by hemp and wood. The stored carbon will be calculated per year and per hectare to provide information on the potential of hemp and wood to provide carbon for the construction industry. For both hemp and wood, the greenhouse gas emissions associated with the provision of the raw materials to the construction industry are calculated, to show both gross- and net data of the storage.

In this study, the carbon stored in the raw materials will be calculated in terms of kg CO_2eq./(ha*yr). The emissions associated with the provision of the raw materials for the construction and insulation industry will be calculated in the same unit. Combined, the numbers can provide information on the average annual net GHG removal potential of wood and hemp raw materials, which can be used in the construction industry. The regional scope selected for this study is Western Europe (mainly Germany and the Netherlands), as this region includes hemp and wood production.

The scope of the study includes the cultivation of the biomass to provision of the raw materials for the building and insulation industry. For wood and hemp, this includes land preparation, seed and seedling production, fertilisation (incl. production), field emissions, harvesting and processing. For wood, the processing included in the greenhouse gas emissions are the trimming, debarking and transport to the saw mill. For hemp the processing includes transport and the decortication and fine opening of the hemp stalks to get fibres and shives. These system boundaries are chosen as at this point, the raw materials can be used for a wide range of applications in construction and insulation materials. The further processing of the raw materials into final construction and insulation materials is not included in this study due to the wide range of different materials which can be produced from the raw materials, performance differences between various final materials and potential differing emissions along the value chain and applications of the raw materials. An overview of the value chain for hemp and wood and a list of applications which the raw materials can be used for is provided in Figure 1. It should be stressed, that this therefore is not an LCA of construction or insulation materials.

3 Methodology

In order to calculate the annual quantity of carbon stored in hemp and wood per hectare, the following methodology is used: the average annual growth of the respective biomass is determined from literature. The usable part of the biomass for the construction industry is determined based on literature. Of the usable part of the biomass, the carbon content is determined, from which the amount of carbon stored in the raw materials can be calculated. This quantity can be converted to the amount of carbon dioxide equivalents which have been removed from the atmosphere, and can be used for the production of long-lasting materials and products.

To quantify the emissions associated with the provision of the raw materials to the construction and insulation industry, literature research has been conducted. Various literature sources have been found which report the emissions associated with the production of wood and hemp. From these literature sources, the emissions associated with the provision of the materials has been calculated. Based on the carbon stored in the raw materials and the emissions associated with the provision of these raw materials, net results can be calculated by subtracting the emissions from the stored carbon in the raw materials (in CO_2eq.). The results are expressed in kg CO_2eq./ha, in order to investigate the potential of hemp and wood to provide carbon to the construction industry and the GHG emissions associated with the provision of the raw materials, normalised per annum and year.

For hemp, a scenario is considered where the cultivation of hemp yields both seeds and straw. In this scenario, an allocation of the greenhouse gas emissions is used to divide the emissions between the seeds and the straw, as the seeds are assumed to be used for food and/or feed purposes and not for construction and insulation materials. As such, the seeds do not constitute a long-lasting material or product, eligible under the carbon removal certification framework. Both an economic and mass allocation has been performed.

The results only consider GHG emissions associated with the provision of the raw materials. Land use, land use change and indirect land use change are outside of the scope of this study. The next chapter provides an overview of the data used for the calculations. In chapter 5 the results of the calculations are presented. Chapter 6 puts the results into context and makes the limitations of the conducted study transparent.

4 Data

This chapter details the data used for the calculations. The chapter is divided in various sections. First the data used for the calculation of the carbon storage potential of hemp and wood raw materials for utilisation in the construction and insulation industry is provided. The next section discusses the data used to determine the greenhouse gas emissions associated with the provision of these raw materials. The results of the calculations are shown in the next chapter.

4.1 Carbon storage data hemp

For hemp, the study published by de Beus et al. (2019) has been used to obtain data for the cultivation yield and the further processing losses of hemp. The hemp cultivation data has been compared to cultivation data in literature (Mylavarapu et al. 2020, MultiHemp 2015, Turunen & van der Werf 2006, González-García et al. 2010, Piotrowski & Carus 2011) and send to HempFlax, the leading hemp processor in Europe with cultivation in The Netherland, Germany and Romania, and La Chanvrière, a leading French agricultural cooperative in hemp cultivation and processing, for validation[1]. Based on the literature and feedback, the straw yield for hemp has been adjusted to 7,8 t dm per hectare. Values for fertilisation may differ depending on a variety of conditions such as the soil composition and intended application of the biomass, therefore a range of emissions associated with the provision of hemp raw materials is reported. The yields are based on hemp strains that are currently listed in the EU seeds catalogue (EC 2022b). The gross carbon removal is influenced by the yield and the amount of raw materials which can be produced from the yield, and is therefore subject to some variation. During the processing of hemp, three raw materials are produced; hemp fibres, hemp shives and hemp dust. All these materials have the potential to be used in the construction and insulation industry. As the processing is purely mechanical, the yield is close to 100%. The fibre yield from the hemp straw is roughly 30%, whereas shives and dust yield are 55% and 15%, respectively.

To determine the carbon content of the hemp straw, dust and shives, literature research has been conducted. For hemp fibres, the carbon content has been reported by de Beus et al. (2019). There it is reported that hemp fibres have 65% cellulose, 15% hemicellulose and 10% lignin. The carbon content of cellulose and hemicellulose is 0.4 kg C/kg, whereas the carbon content of lignin is estimated at 0.6 kg C per kg. Based on this data, the carbon content of hemp fibres is calculated at 0.38 kg C per kg hemp fibres, which corresponds to 1.39 kg CO_2eq./kg fibre.

For hemp shives, the carbon content has been obtained through literature research. The cellulose content of hemp shives is between 0.4 and 0.48, the hemicellulose content is between 0.12 and 0.33 and the lignin content is between 0.18 and 0.28 (Hussain et al. 2018, Vignon et al. 1995, Thomsen et al. 2005, Gandolfi et al. 2013, Garcia-Jaldon et al., Stevulova et al. 2014, Diakité et al., 2021). The average of the composition of the sources detailed above has been used to find the carbon content of hemp shives, which resulted in an average carbon content of 0.41 kg C/kg hemp shives (which corresponds to 1.5 kg CO_2eq./kg shives).

For hemp dust, no literature data on the carbon content was found. Hemp dust are fine particles of either the fibre or the shives which break during the decortication and fine-opening.

[1] Interview, Mark Reinders, CEO HempFlax, 15 December 2022.
Interview, Anais Bobin, Fibres sales manager, 9 March 2023.

As it are fine particles released from the shives or fibres during the processing, it is assumed that the carbon content of the hemp dust is the average of the carbon content of hemp fibres and hemp shives. As such, it is found at 0.39 kg C/kg hemp dust, which corresponds to 1.45 kg CO_2eq./kg dust.

4.2 Carbon storage data wood

The biomass growth of trees can be calculated per tree or based on average data. In this study, average data was chosen as silviculture can vary considerably, furthermore, this reduces uncertainty related to the growth dynamics, tree density, trimming regime and harvesting age. Average data for biomass growth in forests has been obtained from the German Federal Ministery of Food and Agriculture's (BMEL) publication "the forests in Germany" (BMEL, 2015). In this publication, the annual increment for multiple tree species has been determined based on the forestry data collected for the report. From the report, the following annual increments have been used; Spruce (15.3 m^3/(ha*yr)), Fir (16.3 m^3/(ha*yr)), Douglas Fir (18.9 m^3/(ha*yr)), Pine (9.5 m^3/(ha*yr)), Larch (10.7 m^3/(ha*yr)), oak (8.3 m^3/(ha*yr)) and Beech (10.3 m^3/(ha*yr)). The annual increment reported includes deadwood remains, harvesting losses and bark, and increases in growing stock. The report does not provide species specific data for these losses, but an overview of the total amount. From this data, the theoretical use per tree species has been calculated based on the average harvesting losses and bark (17%), and the average deadwood which remains in the forest (9%).

The increase in growing stock represents an accumulation of biomass in the forest, which may or may not be used in future. The report states that for most tree species, the increase in growing stock ranges between 20% and 45% of the increment. Furthermore, the report states that it is difficult to obtain the utilisation possibilities based on the increment, as the increment depends on the present age, diameter structures and planned target diameters or the scheduled harvests. Therefore, two approaches have been used to estimate the theoretical use of wood per hectare. In the first scenario, the combined carbon pool of the forest is assumed to be in steady state. As a consequence of this assumption, all increment is harvested and through subjecting the increment to the fractions lost, an average annual theoretical use can be calculated. The second scenario includes the increase in growing stock as well, for this the percentage of increment which increases the growing stock is subtracted from the increment as well. this percentage is equal to 13% of the increment.

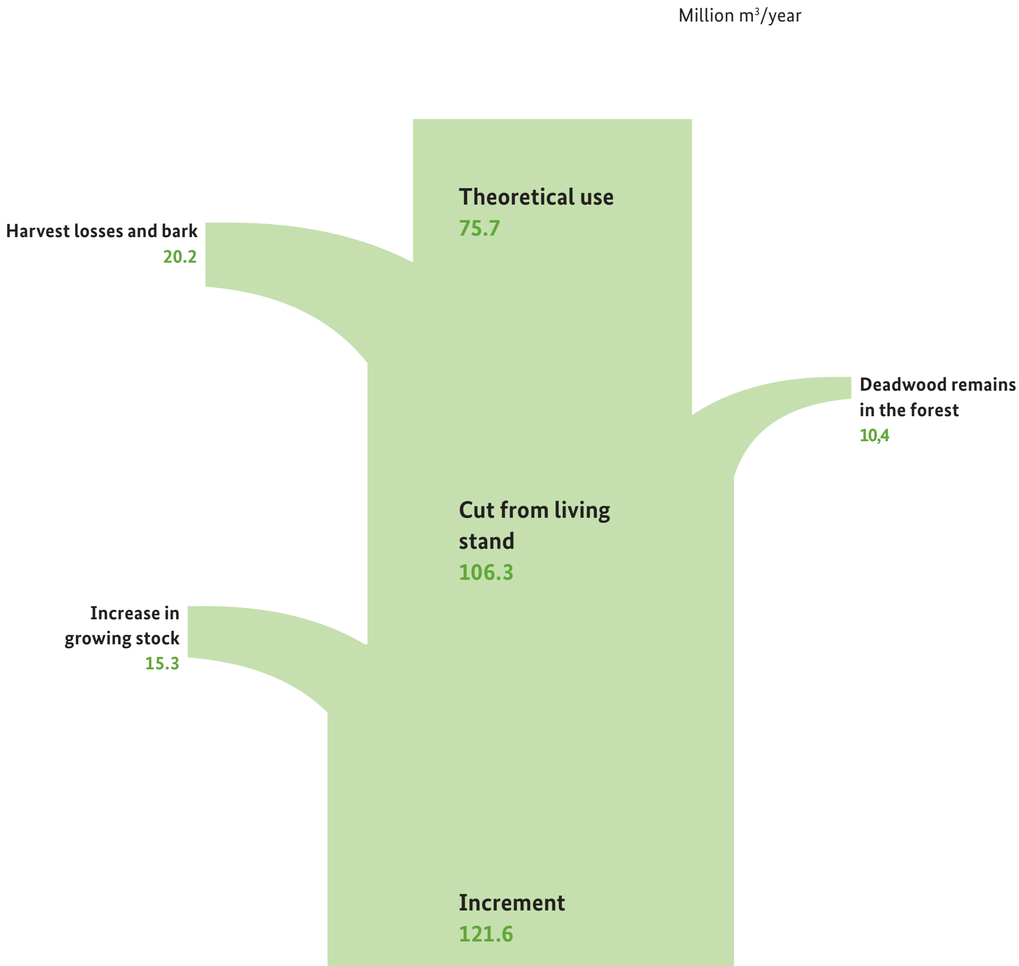


Figure 2. Increment and use of wood (BMEL 2015)

From the numbers reported above, estimates for the theoretical mean annual use of wood per tree species can be computed. It is assumed that practically all theoretical wood use computed this way, can be used in construction and insulation materials. A list of possible construction and insulation applications is provided in chapter 1.

Based on the density of the wood and the carbon content of wood, the amount of carbon stored in the wood, the amount of carbon stored in the wood can be calculated. The following data has been used to calculate the stored carbon. The density of spruce, Fir and Douglas Fir is assumed to be 430 kg/m^3, for Pine and Larch the density is assumed to be 510 kg/m^3. For Oak the density is assumed to be 650 kg and the density of Beech is assumed to be 680 kg/m^3 (Rüter & Diederichs 2012). The average carbon content of wood is assumed to be 50%, based on chemical composition profiles found in the Phyllis database (Phyllis2 2022).

Values found for the increment used in this study have been reviewed using literature to check if the values reported are reasonable. From this literature search it was found that forests increments (and subsequent theoretical use) can vary considerably, but the values reported in the BMEL are in the range of other values reported (Pretzsch et al. 2010, Schnell et al. 2005, Hilmers et al. 2020, Pretzsch et al. 2014, Forest Europe 2020).

4.3 Greenhouse gas emissions hemp

The greenhouse gas emissions associated with the cultivation and processing of hemp fibres has been obtained from the same sources mentioned in chapter 4.1, using the same validation approach and making the same data adjustments. In order to calculate the emissions associated with the hemp raw material provision, which can be obtained from a hectare and used in long-lasting materials or products, the emissions per hectare have been calculated. Since practically all hemp straw can be used in the construction and insulation industry, no allocation between the fibres, shives and dust is required. For the greenhouse gas emissions associated with hemp production, some additional scenarios have been included in the assessment.

The **first and base scenario** is the cultivation of hemp for straw use only. The **second scenario** includes the cultivation of hemp with **organic fertiliser**. The **third scenario** encompasses the **cultivation of hemp for seeds and straw** using a **mass allocation** to divide the burdens of the cultivation over the seeds (yield: 1 t DM/ha) and the straw. The straw yield in this scenario is 6.5 t DM/ha, slightly lower compared to cultivation for straw only. The **fourth scenario** is similar to the third scenario, but an **economic allocation** is used rather than mass allocation. Allocation is used because it is assumed that the hemp seeds will not be used for construction and/or insulation purposes. The error bars in the publication by de Beus et al. (2019) have been used to provide a range of the emissions associated cultivation and processing of hemp, to include uncertainty with regard to fertiliser use as well as annual variations weather conditions potentially affecting yield and fertiliser induced field emissions. Based on the prices obtained from HempFlax[2], the economic allocation factor between the hemp straw and the hemp seeds is 0.5.

4.4 Greenhouse gas emissions wood

Literature has been reviewed to obtain the greenhouse gas emissions associated with the production of wood. From the literature research, it was concluded that various parameters can influence the greenhouse gas emissions associated with the forestry sector, such as tree species, harvesting operations, transportation distance, among others. Therefore, it was decided to compile various values found in literature and derive a range of greenhouse gas emissions potentially associated with the provision of wood to the construction and insulation industry. Such values have been obtained from EcoInvent v3.9 (Wernet et al. 20), Klein et al. (2016) and Karjalainen et al. (2001). Values reported in the above-mentioned literature sources, the minimum, average and maximum emissions associated with the provision of the wood have been computed. EcoInvent reports values for various tree species in the form of 1 m3 sawlog and veneer log, which range roughly between 11 and 15 kg CO_2eq./m^3. Klein et al report on the emissions of the forestry sector in Bayern, with an average emission of 19 kg CO_2eq./m^3 throughout Bayern. Karjalainen and Welling report on the emissions of the forestry sector in Europe, reporting greenhouse gas emissions associated with harvesting, hauling and transport for most EU countries. The highest emissions are in Greece (21.7 kg CO_2eq./m^3), the lowest are reported in Italy (6.3 kg CO_2eq./m^3). The emissions of the German forestry industry are reported at 8.3 kg CO_2eq./m^3. Furthermore, the main sensitivity is associated with the transport. From the data reported above, the minimum, average and maximum emissions per hectare are computed. It should be noted that most data does not differentiate between tree species. Cosola et al. (2016) provide a detailed review of greenhouse gas emissions in the forestry sector using a statistical approach. The greenhouse gas

[2] Personal communication, Mark Reinders, CEO HempFlax, 15 December 2022.

emissions reported by Cosola et al. (2016) are within the range of the values found in the other literature sources.

5 Results and conclusions

This chapter describes the results of the calculations for the carbon storage potential of wood and hemp raw materials for use in construction and insulation industry, as well as the emissions associated with the provision of these raw materials. The chapter will start with the carbon storage, followed by the emissions and finally the values will be combined to show the net results for the provision of the raw materials for the production of long-lasting materials and products. Please note that the further processing of the raw materials into finalised products is not covered in this study. The results in the tables are colour coded, with red indicates a less preferred value compared to the average and green a high value compared to the average. For GHG removals high numbers are good, whereas for emissions, low numbers are preferable.

5.1 Carbon storage results

In the table below, the annualized biomass production, theoretical use, carbon removal and the associated GHG removals are reported for hemp and wood. The increment for wood depends on the tree species, with the Douglas Fir having the highest annual increment, followed by other conifers such as Fir and Spruce. Deciduous trees have a lower annual increment, but have a higher density compared to conifers. For hemp the values are reported for straw production only, as well as for the dual use. It should be noted that the straw yield decreases due to the seed harvest, which reduces the quantity of raw material which can be provided to the construction and insulation industry. The yield loss in dual purpose hemp cultivation can be minimised though advances in harvesting technology. Values in the hemp scenarios which are not coloured, are intermediates obtained from the hemp straw, the sum of these values is coloured.

Table 1. Gross carbon storage results of hemp and wood raw materials for the construction industry

		Conifers					deciduous trees		hemp 7,8t/ha (straw only scenarios)				hemp 6,5 t/ha (seed scenarios)			
	Units	Spruce	fir	douglas fir	pine	Larch	oak	beech	hemp total	*Hemp fibres*	*hemp shives*	*hemp dust*	hemp total	*Hemp fibres*	*hemp shives*	*hemp dust*
Increment	m3/(ha*yr)	15.3	16.3	18.9	9.5	10.7	8.3	10.3	n/a	*n/a*	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*
Cut from living stand	m3/(ha*yr)	13.4	14.2	16.5	8.3	9.4	7.3	9.0	n/a	*n/a*	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*
Theoretical use (stock increase)	m3/(ha*yr)	9.5	10.1	11.8	5.9	6.7	5.2	6.4	n/a	*n/a*	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*
Theoretical use (steady state)	m3/(ha*yr)	11.4	12.2	14.1	7.1	8.0	6.2	7.7								
Dry Density	kg/m3	430	430	430	510	510	650	680	n/a	*n/a*	*n/a*	*n/a*	n/a	*n/a*	*n/a*	*n/a*
Production (stock increase, DM)	kg/(ha*yr)	4,100	4,300	5,100	3,000	3,400	3,400	4,400	7,800	*2,300*	*4,300*	*1,200*	6,500	*2,000*	*3,600*	*1,000*
Production (steady state, DM)	kg/(ha*yr)	4,900	5,200	6,100	3,600	4,100	4,000	5,200	7,800				6,500			
Carbon content	%	0.50	0.50	0.50	0.50	0.50	0.50	0.50		*0.38*	*0.41*	*0.39*	n/a	*0.38*	*0.41*	*0.39*
Carbon removal	kg C/(ha*yr)	2,000	2,200	2,500	1,500	1,700	1,700	2,200	3,100	*900*	*1,800*	*500*	2,600	*800*	*1,500*	*400*
GHG removal (stock increase)	kg CO2eq./(ha*yr)	7,500	8,000	9,300	5,500	6,200	6,200	8,000	11,400	*3,300*	*6,600*	*1,800*	9,500	*2,800*	*5,500*	*1,500*
GHG removal (steady state)	kg CO2eq./(ha*yr)	9,000	9,600	11,200	6,600	7,500	7,400	9,600	11,400	3,300	6,600	1,800	9,500	2,800	5,500	1,500

From a carbon storage point of view (gross removal) hemp and wood raw materials perform similarly. The carbon storage in wood raw materials for construction industry ranges between 11 t CO_2eq/ha for Douglas Fir and 5.5 t CO_2eq/ha for Pine, with most values being found between 7 t CO_2eq/ha and 9 t CO_2eq/ha. For hemp, the amount of carbon stored in the raw materials which can potentially be used in the construction and insulation industry is found between 9.5 and 11.4 t CO_2eq/ha, with the main sensitivity being the straw yield per hectare. Higher straw yields result in more stored carbon per hectare, whereas the opposite holds for lower yields. Due to the differences in production volume and time between the start of the cultivation and the harvest, hemp will fluctuate more compared to wood. Nonetheless, the results suggests that the amount of carbon stored per hectare in raw materials for construction and insulation industry, is similar between hemp and wood, with the hemp raw materials being on the higher end of the values calculated for wood. Although wood DM yields are lower compared to those of hemp, the higher carbon content of wood mean that less wood has to be produced to store a similar amount of carbon in the raw materials.

From the table above, it can also be seen that there is a difference between the modelling approach used for the theoretical use. As the biomass stock is increasing, the steady state approach results in a higher amount of carbon per hectare which could be used in construction and insulation materials. Nonetheless, it should be highlighted that the desire to increase the standing stock in a forest is a political and economic decision which varies over time and by country. Furthermore, it should be considered that a higher standing stock can result in higher increments.

5.2 Greenhouse gas emissions results and net results

In the table below, the results from section 5.1, are included and the findings for the emissions associated with the provision of the raw materials are presented. the top half of the table is associated with the wood increment modelling approach including the increase in wood stock, whereas the bottom part of the table relates to the steady state modelling approach. For hemp, four scenarios are presented which include hemp straw production using mineral fertiliser, hemp straw product using organic fertiliser, hemp straw and seed production using mass allocation and hemp straw and seed production using economic allocation. The allocation is used to divide the greenhouse gas emissions of the cultivation between the straw and the seeds, as the seeds do not have an application in construction and insulation materials. Based on the described methodology, the highest, average and lowest values for the GHG emissions associated with the provision of the raw materials are reported. Together with the carbon storage, this enables the calculation of the net removal of greenhouse gases up to the point at which the raw materials are available for further processing into construction materials. The emissions associated with the further processing are not included in this study. All values in the table above are expressed in kg CO_2eq./ha. Similar to the table above, a colouring scheme is used.

Table 2. Net carbon storage results of hemp and wood raw materials for the construction industry

		Conifers					Deciduous trees		Hemp			
	Units	Spruce	Fir	Douglas fir	Pine	Larch	Oak	Beech	Straw	Straw (organic fertiliser)	*Straw + Seeds (mass)*	*Straw + Seeds (eco)*
GHG removal (stock increase)	kg CO2eq./(ha*yr)	7,500	8,000	9,300	5,500	6,200	6,200	8,000	11,400	11,400	9,500	9,500
Average emissions (stock increase)	kg CO2eq./(ha*yr)	129	138	160	83	91	92	81	2,500	2,200	2,200	1,500
Max emissions (stock increase)	kg CO2eq./(ha*yr)	207	220	255	128	145	173	122	2,900	2,400	2,500	1,700
Min emissions (stock increase)	kg CO2eq./(ha*yr)	60	64	74	37	42	50	33	2,100	2,100	1,800	1,300
Net removal (average) (stock increase)	kg CO2eq./(ha*yr)	7,400	7,900	9,100	5,400	6,100	6,100	7,900	8,900	9,200	7,300	8,000
Net removal (max) (stock increase)	kg CO2eq./(ha*yr)	7,300	7,800	9,000	5,400	6,100	6,000	7,900	8,500	9,000	7,000	7,800
Net removal (min) (stock increase)	kg CO2eq./(ha*yr)	7,400	7,900	9,200	5,500	6,200	6,100	8,000	9,300	9,300	7,700	8,100
Steady state forestry												
GHG removal (steady state)	kg CO2eq./(ha*yr)	9,000	9,600	11,200	6,600	7,500	7,400	9,600	11,400	11,400	9,500	9,500
Average emissions (steady state)	kg CO2eq./(ha*yr)	155	167	192	99	109	109	95	2,500	2,200	2,200	1,500
Max emissions (steady state)	kg CO2eq./(ha*yr)	247	266	305	154	174	203	144	2,900	2,400	2,500	1,700
Min emissions (steady state)	kg CO2eq./(ha*yr)	72	77	89	45	51	59	38	2,100	2,100	1,800	1,300
Net removal (average) (steady state)	kg CO2eq./(ha*yr)	8,900	9,500	11,000	6,500	7,400	7,300	9,500	8,900	9,200	7,300	8,000
Net removal (max) (steady state)	kg CO2eq./(ha*yr)	8,800	9,400	10,900	6,500	7,300	7,200	9,500	8,500	9,000	7,000	7,800
Net removal (min) (steady state)	kg CO2eq./(ha*yr)	9,000	9,500	11,000	6,600	7,400	7,300	9,600	9,300	9,300	7,700	8,100

From the table above, it can be seen that the GHG emissions associated with the provision of wood raw materials is lower compared to the GHG emissions associated with the provision of hemp raw materials. Therefore, it can be concluded that the production of hemp is associated with high inputs and high outputs, whereas the production of wood is associated with low inputs. These results are in line with the expectation as agricultural processes require significantly larger inputs of for example fertiliser, compared to forestry. The production and utilisation of fertilisers is one of the main hotspots in the cultivation of hemp (de Beus et al. 2019).

The net results are calculated by subtracting the emissions associated with the provision of the raw materials from the carbon stored in the raw materials (in CO_2eq.). Therefore, the higher the values for the net results, the more carbon is stored in raw materials which can be made available per hectare for long-lasting materials or products. Similar to the results of the stored carbon, the net emissions are sensitive towards the modelling approach for the theoretical use of wood per hectare. When growing stocks are increasing at the average rate in Germany, hemp shows net removal values similar to the upper range of wood. The difference between the net results for the Douglas fir and hemp cultivation for “straw only” are insignificant. From the results using the steady state approach, it can be concluded that the net removal of GHG associated with the provision of wood and hemp to the construction and insulation industry is similar. As such, hemp shares properties with wood in the potential to supply the construction and insulation industry with a raw material which removes more GHGs than it emits in the provision.

It is interesting to note that the dual-purpose hemp, cultivation of hemp for straw and seeds, has lower net results compared to the single purpose hemp. From this observation it can be concluded that the loss of straw yield, due to the harvest of the seeds, is higher compared to the part of the GHG emissions which are allocated to the seeds. In other words, the dual cultivation purpose stores less carbon in raw materials which can be used in the construction industry. This effect is more pronounced for mass allocation, compared to economic allocation, because the value of seeds is relatively high compared to the value of the straw. as a consequence, economic allocation attributes less GHG emissions to the straw. it should be noted that the carbon stored in the seeds is not included in this assessment as it is assumed that this carbon is not used in the construction industry.

Finally, to summarise, hemp can store carbon as efficient as wood in construction materials. Both hemp and wood can provide raw materials, which can be further converted into construction and insulation materials, with a net GHG removal per hectare in the range of 5.5 to 11 t CO_2eq./ha. These values include the cultivation, transport and initial processing of the raw materials. For hemp, the emissions associated with the fractionation of the straw into fibres, shives and dust is included. For wood, the emissions associated with the debarking and transport to the next processing facility are included. It should also be noted that the range of the results reported in this study is relatively high, as many aspects play a role in the production of the raw materials. Nonetheless, the study shows that the use of hemp and wood raw materials (in long-lasting materials and products) can recontribute to net carbon dioxide removal and thus should both be eligible for certification in the carbon removal certification framework, provided that the further processing into the final materials and products releases less GHG emissions than the net carbon dioxide equivalent removed during the provision of the raw materials. Production of the final materials and products is not included in this study due to the large diversity of production processes and value chain specificity of emissions associated with these processes.

6 Discussion and limitations

In this chapter, the results of the study are briefly discussed and several limitations of the study are highlighted.

Firstly, due to various reasons, it should be noted that this study does not provide information on the environmental preferability of using wood or hemp based raw materials for the production of construction and insulation materials. These reasons include, among others;

- The production process of the construction material itself is not included in the assessment;
- There may be functional differences between the construction material produced from wood compared to a similar construction material produced from hemp;
- Differing final products may be produced from the raw materials;
- This study focusses on GHG emissions solely, and does not consider other environmental impacts associated with the provision of the raw materials;
- Local conditions influence the biomass yield, which has been shown to have a large influence on the annual carbon storage potential per hectare.

The study has calculated the potential of a hectare of wood and hemp to transfer carbon from the biosphere to materials which can be used in the construction and insulation industry. The potential of a hectare of wood and hemp to provide carbon to the construction industry, including greenhouse gas emissions associated with the production, is similar. This study does not enable conclusions on the cumulative quantity of carbon which can be transferred, as the demand for such products is not included in this assessment.

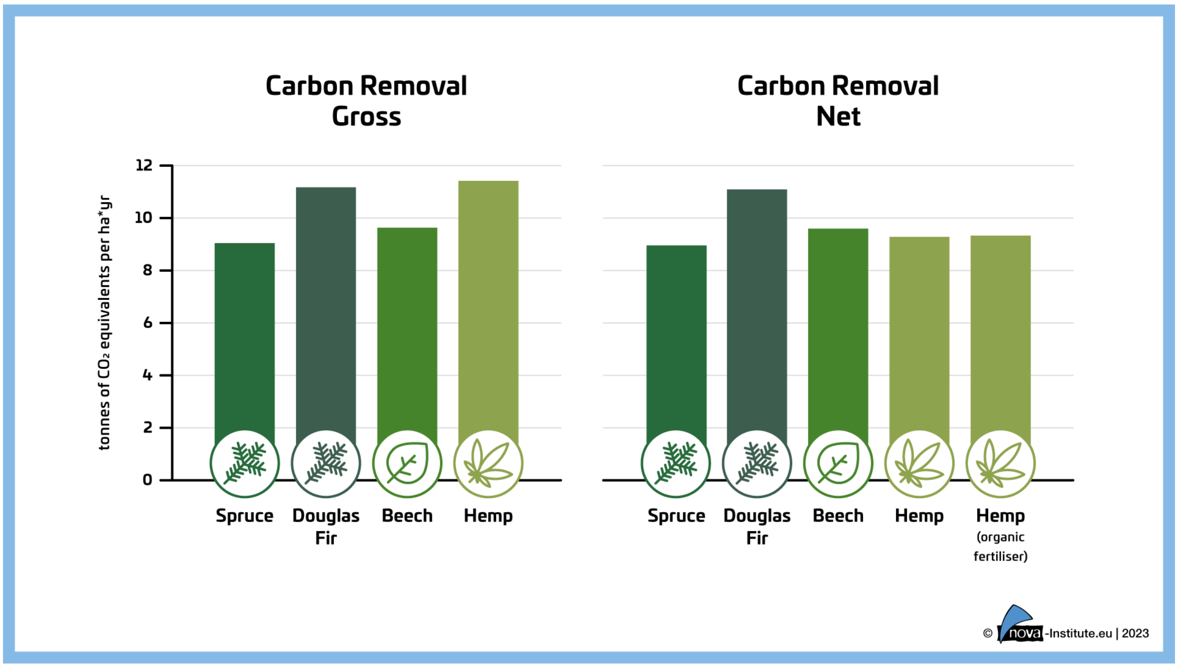


Figure 3. Gross and net carbon removal of hemp and wood per hectare and year.

The results of the study clearly show some differences between the production of hemp and wood based raw materials for the construction industry. The provision of wood is associated with low GHG emissions (per hectare) and a long period between seeding and harvest, rotation periods can be over 100 years. Due to the long rotation periods, the annual supply of wood is unlikely to show large year-to-year fluctuations. Another effect of the long rotation periods is that the management practices may change during the rotation period, which increases uncertainty related to the yield and GHG emissions. Nonetheless, the GHG emissions associated with the provision of wood are mainly related to the harvesting and transport, which occur to the end of the rotation period. Furthermore, wood has the advantage that not all annual production has to be harvested. When the annual increment is higher than the annual felling, the standing volume of wood in the forest increases and can be harvested later.

Hemp has to be harvested annually; the growing period lasts around five to six months. As such, annual production volume can show larger year-to-year variations, which can be beneficial (supply can be increased more quickly) but also detrimental (supply chain stability). Hemp is an annual crop which, like other cereals and oilseeds, is inevitably associated with greenhouse gas emissions (per hectare) linked to the use of fertilisers. However, hemp can also remove large quantities of carbon from the atmosphere during the growing period, similar to the carbon removal of fast-growing trees, for example the Douglas Fir. Moreover, as the growing period is only part of the year, there is the possibility to grow a winter crop for the other half of the year on the same hectare, increasing land use efficiency. This possibility and the effects of it are outside of the scope of this study. Nonetheless, this is a possibility worth further study.

The carbon storage potential and the GHG associated with the provision of the raw materials are subject to uncertainties. Therefore, the values reported in this study should be interpreted as a range. Uncertainties are mainly related to the yield/increment per hectare, management practices, fertilisation (mainly hemp), tree species, use/increment ratio (wood), regional conditions and transportation distance. This study does not include GHG emissions or removals associated with land use, direct land use change, indirect land use change and soil organic matter changes.

7 Literature

BMEL (Federal Ministry of Food and Agriculture), (2015). The Forests in Germany - Selected Results of the Third National Forest Inventory. BMEL, Berlin, Germany.

Cosola, G., Grigolato, S., Ackerman, P., Monterotti, S., Cavalli, R., (2016). Carbon Footprint of Forest operations under Different Management Regimes. Croatian Journal of Forest Engineering, 37, 201-217.

de Beus, N., Carus, M., Barth, M., (2019). Carbon Footprint and Sustainability of Different Natural Fibres for Biocomposites and Insulation Material - Study providing data for the automotive and insulation industry, nova-Institut, Hürth, Germany, available at: https://renewable-carbon.eu/publications/product/carbon-footprint-and-sustainability-of-different-natural-fibres-for-biocomposites-and-insulation-material-%E2%88%92-full-version-update-2019/

DG Agri, Directorate-General Agriculture and Rural Development, (2022). Hemp. Available at: https://agriculture.ec.europa.eu/farming/crop-productions-and-plant-based-products/hemp_en, last accessed on 22-02-2023

DG GROW, Directorate-General Internal Market, Industry, Entrepreneurship and SMEs, (2023). Buildings and construction. Available at: https://single-market-economy.ec.europa.eu/industry/sustainability/buildings-and-construction_en

Diakité, M. S., Lenormand, H., Lequart, V., Arufe, S., Martin, P., & Leblanc, N. (2021). Cell Wall Composition of Hemp Shiv Determined by Physical and Chemical Approaches. Molecules (Basel, Switzerland), 26(21), 6334. https://doi.org/10.3390/molecules26216334

EC, European Commission (2020). A Renovation Wave for Europe - greening our buildings, creating jobs, improving lives. Communication 662 Final, 14-10-2020, Brussels, Belgium.

EC, European Commission (2022). Proposal for a Regulation on an EU certification for carbon removals, communication 672 Final, 30-11-2022, Brussels, Belgium. https://climate.ec.europa.eu/document/fad4a049-ff98-476f-b626-b46c6afdded3_en

EC, European Commission (2022b), Plant variety catalogues, databases & information systems. available at: https://food.ec.europa.eu/plants/plant-reproductive-material/plant-variety-catalogues-databases-information-systems_en

Forest Europe, (2020). State of Europe's Forests 2020.

Gandolfi, S., Ottolina, G., Riva, S., Pedrocchi Fantoni, G., Patel, I., (2013). Complete Chemical Analysis of Carmagnola Hemp Hurds and Structural Features of Its Components. BioResources, 8, 2641–2656, https://bioresources.cnr.ncsu.edu/resources/complete-chemical-analysis-of-carmagnola-hemp-hurds-and-structural-features-of-its-components/

Garcia-Jaldon C. (1995). Caractérisation Morphologique et Chimique du Chanvre (*Cannabis sativa*): Prétraitement à la Vapeur et Valorisation. Ph.D. Thesis, University Joseph Fourier; Grenoble, France.

González-García, S., Hospido, A., Feijoo, G. & Moreira, M. T., 2010. Life cycle assessment of raw materials for non-wood pulp mills: Hemp and flax. Resources, Conservation and Recycling, 54(11), pp.923–930.

Hilmers, T., Biber, P., Knoke, T., Pretsche, H., (2020). Assessing transformation scenarios from pure Norway spruce to mixed uneven-aged forests in mountain areas. European Journal of Forest Resesearch 139, 567–584. https://doi.org/10.1007/s10342-020-01270-y

Hussain, A., Calabria-Holley, J., Jiang, Y., Lawrance, m., (2018). Modification of hemp shiv properties using water-repellent sol–gel coatings. Journal of Sol-Gel Science and Technology, 86, 187–197. https://doi.org/10.1007/s10971-018-4621-2

Karjalainen, T., Zimmer, B., Berg, S., Welling, J., Schwaiger, H., Finér, L., Cortijo, P., (2001). Energy, Carbon and Other Material Flows in the Life Cycle Assessment of Forestry and Forest Products Achievements of the Working Group 1 of the COST Action E9. European Forest Institute, discussion paper 10, Joensuu, Finland, ISSN: 1455-6936.

Klein, D., Wolf, C., Schulz, C., Weber-Blaschke, G., (2016). Environmental impacts of various biomass supply chains for the provision of raw wood in Bavaria, Germany, with focus on climate change. Science of the Total Environment, 539, 45-60. https://doi.org/10.1016/j.scitotenv.2015.08.087

Multihemp, 2015. Multihemp project. Available at: http://multihemp.eu/.

Mylavarapu, R. S., Brym, Z., Monserrate, L., & Mulvaney, M. J. (2020). Hemp Fertilization: Current Knowledge, Gaps and Efforts in Florida: A 2020 Report: SL476/SS689, 8/2020. *EDIS*, *2020*(4). https://doi.org/10.32473/edis-ss689-2020

Phyllis2, (2022). Database for (treated) biomass, algae, feestocks for biogas production and biochar, https://phyllis.nl. TNO Biobased and Circular Technologies.

Piotrowski, S. & Carus, M., 2011. Ecological benefits of hemp and flax cultivation and products. Nova-Institute, Hürth.

Pretzsch, H., Biber, P., Schütze, G., Uhl, E., Rötzer, T., (2014). Forest stand growth dynamics in Central Europe have accelerated since 1870. Nature Communications **5**, 4967, https://doi.org/10.1038/ncomms5967

Pretzsch, H., Block, J., Dieler, J., Dong, P.H., Kohnle, U., Nagel, J., Spellmann, H., Zingg, A., (2010). Comparison between the productivity of pure and mixed stands of Norway spruce and European beech along an ecological gradient. Annals of Forest Science, 67, 712, https://doi.org/10.1051/forest/2010037

Rüter, S. and S. Diederichs, (2012). Ökobilanz-Basisdaten für Bauprodukte aus Holz. Final project report, Grant Agreement Nummer: 22028808, BMELV.

Schnell, A., and A., Bauer, (2005). Die zweite Bundeswaldinventur 2022: Ergebnisse für Bayern. LWF (Bayerische Landesanstalt für Wald und Forstwirtschaft, Lerchl Druck, Freising, ISSN: 0945-8131.

Stevulova, N., Cigasova, J., Estokova, A., Terpakova, E., Geffert, A., Kacik, F., Singovszka, E., & Holub, M. (2014). Properties Characterization of Chemically Modified Hemp Hurds. Materials (Basel, Switzerland), 7(12), 8131–8150. https://doi.org/10.3390/ma7128131

Thomsen, A. B., Rasmussen, S. K., Bohn, V., Nielsen, K. V., Thygesen, A. (2005). Hemp raw materials: The effect of cultivar, growth conditions and pretreatment on the chemical composition of the fibres. (Denmark. Forskningscenter Risoe. Risoe-R; No. 1507(EN)).s

Turunen, L. & van der Werf, H.M.G., 2006. Life Cycle Analysis of Hemp Textile Yarn, Comparison of Three Hemp Fiber Processing Scenarios and a Flax Scenario. French National Institute for Agronomy Research, Rennes.

Vignon, M.R., Garcia-Jaldon, C., Dupeyre, D., (1995) Steam explosion of woody hemp Chènevotte. International Journal of Biological Macromolecules, 17, 6, 395-404, https://doi.org/10.1016/0141-8130(96)81852-6

Wernet, G., Bauer, C., Steubing, B., Reinhard, J., Moreno-Ruiz, E., and Weidema, B., (2016). The ecoinvent database version 3 (part I): overview and methodology. The International Journal of Life Cycle Assessment, [online] 21(9), pp.1218–1230. Available at: http://link.springer.com/10.1007/s11367-016-1087-8