Industrial Hemp – A review of economic potential, carbon sequestration, and bioremediation

An output of the Portland State Hemp Collaborative and the Institute of Sustainable Solutions at Portland State University.

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Executive Summary

Introduction

Cannabis sativa is a domesticated crop with a history of over 12,000 years. Today in the U.S. we classify the plant as Marijuana or Hemp based on the concentration of the psychoactive Delta 9-tetrahydrocannabinol (THC). Hemp has very low THC (0.3% or less on a dry weight basis) and can be used to produce oil, food, fiber etc. with over 50,000 end uses. The criminalization of the Hemp plant without differentiating between hemp and marijuana in the 1970's and 1980s eliminated hemp products from our economic system but the legalizing of the hemp plant by the Federal government in 2018 is leading to a rapid growth in the hemp industry focused on building materials, industrial textiles, consumer textiles, bioplastics, packaging, and food.

Since the hemp economy is relatively new, there is also an opportunity to ensure it is developed in a way that provides economic opportunities, especially for communities of color that have traditionally been disenfranchised by the plant, and helps close racial equity gaps. The versatile hemp plant sequesters significant carbon and has a strong potential to contribute to efforts to tackle climate change. The plant also has phytoremediation properties, the ability to remove chemical pollution from the soil, and can be used to remediate brownfields and other polluted lands.

Portland, Oregon is well positioned to contribute to and benefit from a processing and fabrication industry based on industrial hemp given the potential to lower the carbon footprint of materials and generate green jobs. At the same time given that this is a "new" industry there are significant unknowns about the economic viability of the industry and the environmental benefits. In this report we explore the factors that impact the economic feasibility of processing hemp, present a detailed analysis of the carbon benefits of selected hemp material and conduct a literature review on the phytoremediation potential of hemp.

Economics Analysis

Hemp fiber can provide many sustainable products for consumer and industrial use, but first the usable fiber must be separated with a decorticator. Since decorticators are necessary to make industrial hemp fiber, we conduct the economic analysis by constructing a scenario builder in Excel to model the economic feasibility of purchasing and operating a decorticator. We then use this tool to investigate the economic feasibility of obtaining a decorticator for Oregon's local hemp economy and examine annual net revenue and years to profitability across multiple decorticators given varying parameters about the costs, outputs and prices.

We considered four decorticators; LaRoche, HempTrain, FiberTrack 660, Hurdmaster and analyze feasibility over eight different scenarios defined by input amount/acres dedicated to industrial hemp, selected outputs (hurd or hurd and bast) and prices (low price scenario and high price scenario). We find that for 1000 tons of input (500 acres at a yield of 2 T/acre) all decorticators would be profitable within five years given high prices and outputs of hurd and bast. The results also show that if selling only bast, at high prices, profitability can be achieved within 4-9 years for all decorticator (for 1000 tons).

Overall, across all the simulations we find that processing industrial hemp is likely to be profitable. We also find that the FiberTrack 660 has the highest net revenue, but it's important to note that the economic feasibility is more sensitive to prices, cost, and other parameters than choice of decorticator. Therefore, each of the four decorticators is likely to be profitable and we recommend market studies to understand likely output prices and farmers surveys to inform decisions about likely yields and available amounts of inputs.

Carbon Calculation

The carbon footprint of industrial hemp and hemp-lime insulation was estimated using Life Cycle Assessment (LCA) methodology limited to the CO2 emissions expected to occur during the production of the raw materials, production of the commercial material, and installation.

We first calculate the CO2 sequestered by industrial hemp by determining the chemical composition of different plant varietals and we find that cultivation of 1 mT of industrial hemp is expected to sequester 1.37 to 1.6 mT of CO2. This implies 3.151-3.68 mT of carbon dioxide is sequestered per hectare (ha) assuming a conservative estimate of 2.3 mT of industrial hemp harvested per hectare. We then model the production of hemp hurd and find that one ton of hemp hurd sequesters between 0.219 and 0.763 mT of CO2.

We then extend the analysis to explore the carbon footprint of hemp-lime insulation, a buzz-worthy sustainable construction material made from hemp hurd, lime binder, and water. We estimate that 1 m^2 of wall insulated with hemp lime would result in sequestering 10 kg of CO2 in the best case to emitting 6.24 kg of CO2 in the worst case. In contrast, a 1 m^2 section of wall insulated with fiberglass is expected to result in 47.25 kg of CO2e. Using hemp-lime instead of fiberglass insulation will result in significantly less CO2 emissions.

These results affirm that hemp-based construction materials would have a positive environmental impact in terms of CO2 emissions, can be a sustainable alternative to traditional insulation materials and could contribute to emissions reduction goals in Oregon's Climate Action Plan.

Brownfield Remediation

The third part of this study focused on exploring if the phytoremediation properties of hemp make the plant an attractive option for brownfield remediation. Brownfields, land that has contaminated soil from chemicals leaching into the soil, need effective management and restoration that can be complicated and costly. Phytoremediating plants naturally extract contaminants from the soil and can be used for brownfield restoration in certain conditions. Oregon has 176 active brownfield sites, 46 of which are in Multanomah County and Portland has been identified as an urban area with a high capacity for brownfield redevelopment highlighting the potential to use hemp to assit with brownfield remediation.

For this study, we conducted a literature review to (1) identify the potential for industrial hemp to remediate brownfields and (2) explore the usability of contaminated biomass from growing industrial hemp on brownfield sites. Based on the literature reviewed, industrial hemp accumulates low concentrations of heavy metals (such as Cadmium (Cd), Copper (Cu), Led (Pb), and Zinc (Sn)) within the harvestable parts of the plant. The phytoremediation potential can be increased with the use of rhizobacteria, genetic engineering, and increasing bioavailability of heavy metals. At the same time the uptake of HM in lower concentrations is a benefit in terms of post-remediation use. We also find that given the low-concentrations of uptake of heavy metals, hemp used to remediate brown fields can be used subsequently but in some cases may need proper management based on toxicity levels.

1. Overview and History of Hemp

Cannabis sativa is a domesticated crop with a history of over 12,000 years that has been cultivated around the world (Ren et al. 2021). Today in the U.S. we classify the plant as Marijuana and Hemp. Marijuana contains the psychoactive Delta 9-tetrahydrocannabinol (THC) and is grown for recreational or medicinal adult use. In contrast, Hemp has very low THC (0.3% or less on a dry weight basis) and is grown for fiber, oil, as a food source and more. Cherney and Small (2016) state that there are over 50,000 uses for hemp and early uses included paper, textiles, rope, canvas sails, and folk remedies. The versatile hemp plant sequesters significant carbon and has a strong potential to contribute to efforts to tackle climate change. The plant also has phytoremediation properties and has the ability to help remediate brownfields and other polluted lands.

While hemp has been used around the world for millennia, the war on drugs in the 1970’s and 1980’s criminalized the plant without differentiating between hemp and marijuana and the THC content or final uses. As a result, the U.S. has not had a commercial/industrial hemp industry until the Federal government legalized industrial hemp in 2018. The legalization of hemp led to nascent but rapidly growing industrial/commercial hemp economy.

Portland, Oregon is well positioned to contribute to and benefit from a processing and fabrication industry based on industrial hemp given the potential to lower the carbon footprint of materials and generate green jobs. Also, local processing and fabrication of industrial hemp could stimulate demand by eliminating import shipping costs. Since the hemp economy is relatively new, there is also an opportunity to ensure it is developed in a way that helps close racial equity gaps within Portland and surrounding areas and provide opportunities for communities that have traditionally been disenfranchised by the plant.

At the same time given that this is a “new” industry there are significant unknowns about the economic viability of the industry and the environmental benefits. In this study we explore the factors that impact the economic feasibility of processing hemp, present a detailed analysis of the carbon benefits of selected hemp material and conduct a literature review on the phytoremediation potential of hemp.

Section 2 presents an overview of the history of hemp in the United States, Section 3 explores the factors that impact the economic feasibility of operating a hemp decorticator, Section 4 analyzes the carbon benefits of hemp-lime as a building material, Section 5 presents the phytoremediation aspects of hemp and Section 6 concludes with a summary of the key findings.

1.1. History of Industrial Hemp

Hemp is a non-intoxicating cultivar of Cannabis Sativa that by U.S. standards contains no more than 0.3% of the cannabinoid THC in any part of the plant (U.S. NIH, 2020). Hemp is genetically distinct from Marijuana, and is subject to its own set of regulatory requirements. In the early 1900s, the intoxicating effects of Cannabis concerned policymakers, resulting in several states prohibiting its use. After the Commissioner of the Federal Bureau of Narcotics, Harry Anslinger, deployed a national anti-marijuana campaign, the U.S. federal government passed the Marijuana Tax Act (MTA) of 1937 (U.S. Customs and Border Patrol). The MTA was the first national legislation imposing restrictions on Cannabis production, requiring marijuana importers to register with the U.S. Customs and Border Control and pay $24 tax per year.

In the 1970s, the Controlled Substances Act (CSA) signed by President Nixon and followed by the "war on drugs" in the 1980s and the Comprehensive Crime Control Act (CCCA) signed by President Regan pushed hemp out of the economic system. Hemp and marijuana were indistinguishable to regulators at that time, so the MTA, CSA, and CCCA imposed regulation on both hemp and marijuana. Under the CSA, Cannabis became a control I substance, prohibiting consumption, production, and distribution and the CCCA increased penalties for the possession of cannabis.

Organizations and communities advocated for the deregulation of Cannabis. In 2014, the Agricultural Act established the first federal definition for industrial hemp, a varietal of Cannabis Sativa L. with no more than 0.3% delta-9 THC, the intoxicating chemical found in marijuana. The legislature also legalized production of industrial hemp for research purposes within highly regulated pilot programs. Then in 2018, the Agriculture Improvement Act removed industrial hemp from the controlled substance list established under the CSA and transferred the regulatory authority of industrial hemp from the DEA to the U.S. Department of Agriculture (USDA) and the Food Drug Association (FDA). At this point legal protection was established to protect commercial production of industrial hemp nationwide.

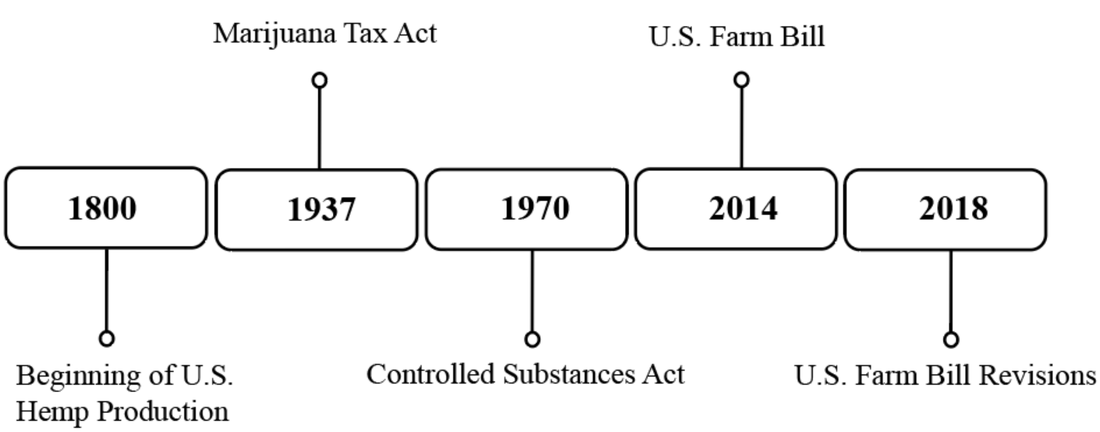


Figure 1: Timeline of Hemp Regulations in the United States

In 2018, Farm Bill removed hemp from the controlled substances list and allowed states to issue licenses to grow hemp. Regulations varied by state and not all states had implemented hemp programs. In 2016, under the 2014 Farm Bill, an estimated 9700 acres of hemp were grown in the US (Allen 2020). This estimate increased to about 25,000 acres in 2017 and 75,000 acres in 2018 before that year's Farm bill was enacted. In hemp's first growing season as a federally legal plant, 34 states were issuing growing licenses and for an estimated 400,000 acres of hemp (Allen 2020, Allen and Whitney, 2019).

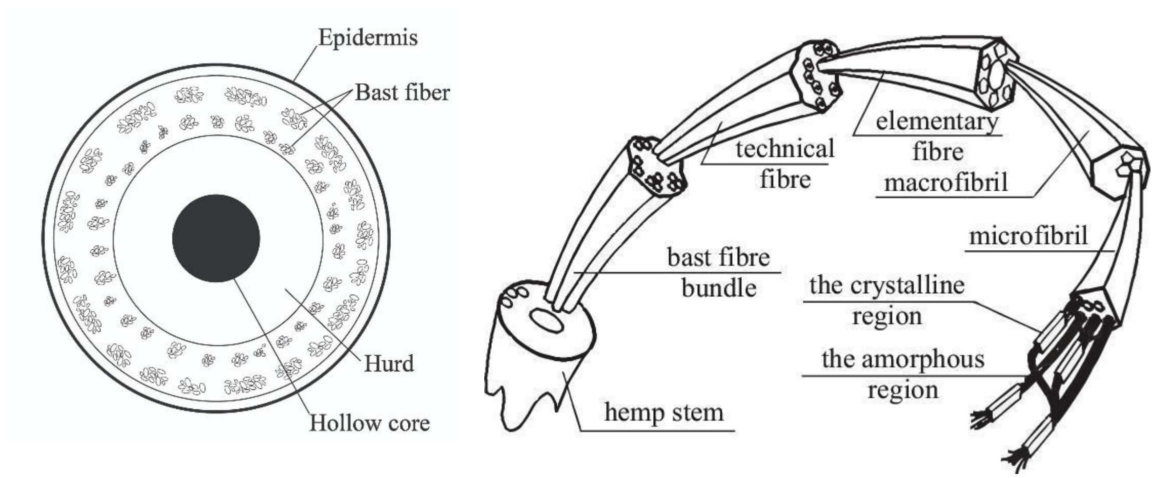
Commercial production of hemp is legal in the U.S., and the industry is regulated by state agencies. Hemp growers, processors, and handlers must have a license before growing or handling hemp (ODA, 2022). To obtain a license in Oregon, a grower must submit an application with the Oregon Department of Agriculture (ODA) and all key participants must complete a full background check and fingerprinting. Licensed growers are required to complete pre-harvest THC testing in a lab licensed by the Oregon Liquor Control Commission (OLCC) and post-harvest testing by an ORELAP-accredited facility. Currently post-harvest testing procedures include testing for pesticides, moisture content, cannabinoid potency, and mycotoxins; after March 1, 2023, hemp biomass will also be tested for heavy metals and microbiological contaminants (ODA, 2022).

Since the hemp economy is resurging since legalization in 2018, there is also an opportunity to ensure it is developed in a way that provides equitable economic opportunities. Given that communities of color have traditionally been disenfranchised by cannabis, the new industrial hemp economy provides an opportunity to helps close racial equity gaps. The legalization also provides opportunities for indigenous tribes to reclaim the plant that has historically been used extensively across the country and the seeds of these efforts are already sprouting (Laduke 2021).

Portland, Oregon is well positioned to contribute to and benefit from a processing and fabrication industry based on industrial hemp given the potential to lower the carbon footprint of materials and generate green jobs. At the same time given that this is a "new" industry there are significant unknowns about the economic viability of the industry and the environmental benefits. In this report we explore the factors that impact the economic feasibility of processing hemp, present a detailed analysis of the carbon benefits of selected hemp material and conduct a literature review on the phytoremediation potential of hemp.

2. The hemp plant and potential industrial hemp uses

Industrial hemp is a rapidly growing plant that can grow without herbicides and pesticides. The plant also uses low amounts of water compared to crops like cotton (Hawken 2017). There are four types of varieties of industrial hemp: flower, oilseed/grain, fiber, and dual-purpose varieties (Jeliazkov, 2019). Each variety has unique genetic qualities, yield, cultivation requirements, and commercial applications. Figure 2 presents shows the composition of the hemp plant.



(Jensen, 2022) (Kaczmar, 2011)

Figure 2: Composition of the Hemp Plant

The amount of bast fiber and hurd within a given plant varies depending on the genotype and growing conditions. Although fiber varieties are often selected by growers seeking to maximize harvest of hurd, high hurd content has been observed in some flower genotypes. A recent field study found high hurd content in the Blue Genius and Cherry Wine plants which are flower varieties (Amarasinghe, 2022). The fiber varietals Jin Ma, Tetra, Carmagnola, Eletta campana, Fibranova, and Bialobrzeski are fibrous varietals that have been identified to have a high proportion of hurd (Darby, 2018; Luhr, 2018; Amarasinghe, 2022).

In general, fiber varieties are grown when fiber or hurd is the primary commodity harvested, flower varieties are grown when cannabinoids are the primary commodity harvested, and Oilseed/grain varieties are grown when seeds are the primary commodity harvested (Jeliazkov et. al, 2019). Dual-purpose varieties are well-suited to harvest multiple commodities and have been shown to outperform fiber varieties in terms of gross profit (Das, 2020). Figure 3 presents a summary of the commercial applications of the different varietals.

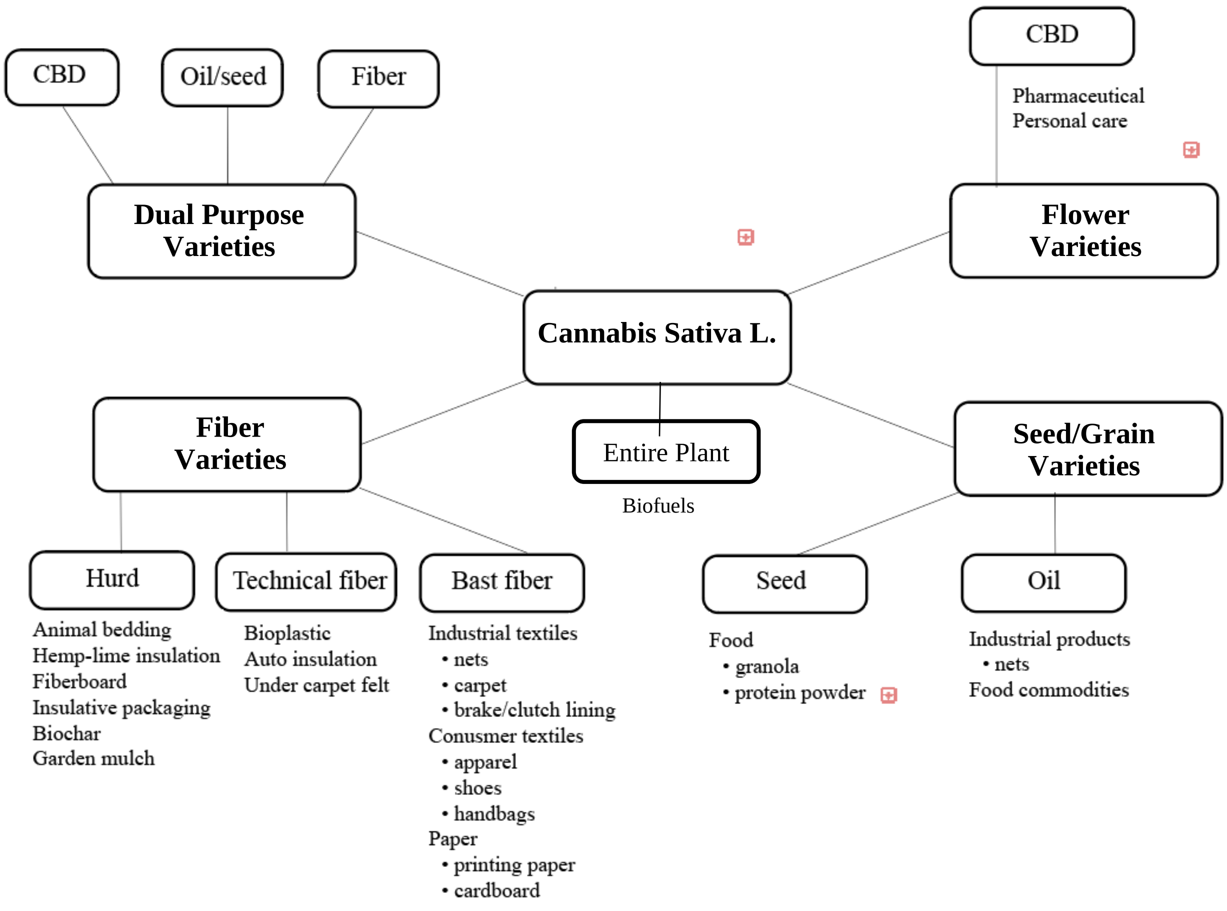


Figure 3: Outputs from the Hemp Plant

3. Economic Analysis of Decorticators

3.1. Analysis Framework

In this section we explore the economic feasibility of investing in a hemp fiber decorticator. Hemp fiber can provide many valuable and sustainable products for consumer and industrial use, but first the harvested hemp must undergo a process to separate the usable fiber from the rest of the plant. The separation and sorting of hemp fiber is done with specialized equipment called a decorticator, which removes the woody (hurd) and fine (bast) fibers from the hemp plant for commercial and industrial use. Since decorticators are necessary to make industrial hemp fiber available, we build our analysis around the purchase of decorticator and investigate the economic feasibility of obtaining one for Oregon's local hemp economy by constructing a scenario builder for decorticators of various costs and capabilities. This provides a framework to examine how different scenarios for key fixed and variable costs impact the time to payback or break even for a particular decorticator which is a key influencing factor in its investment.

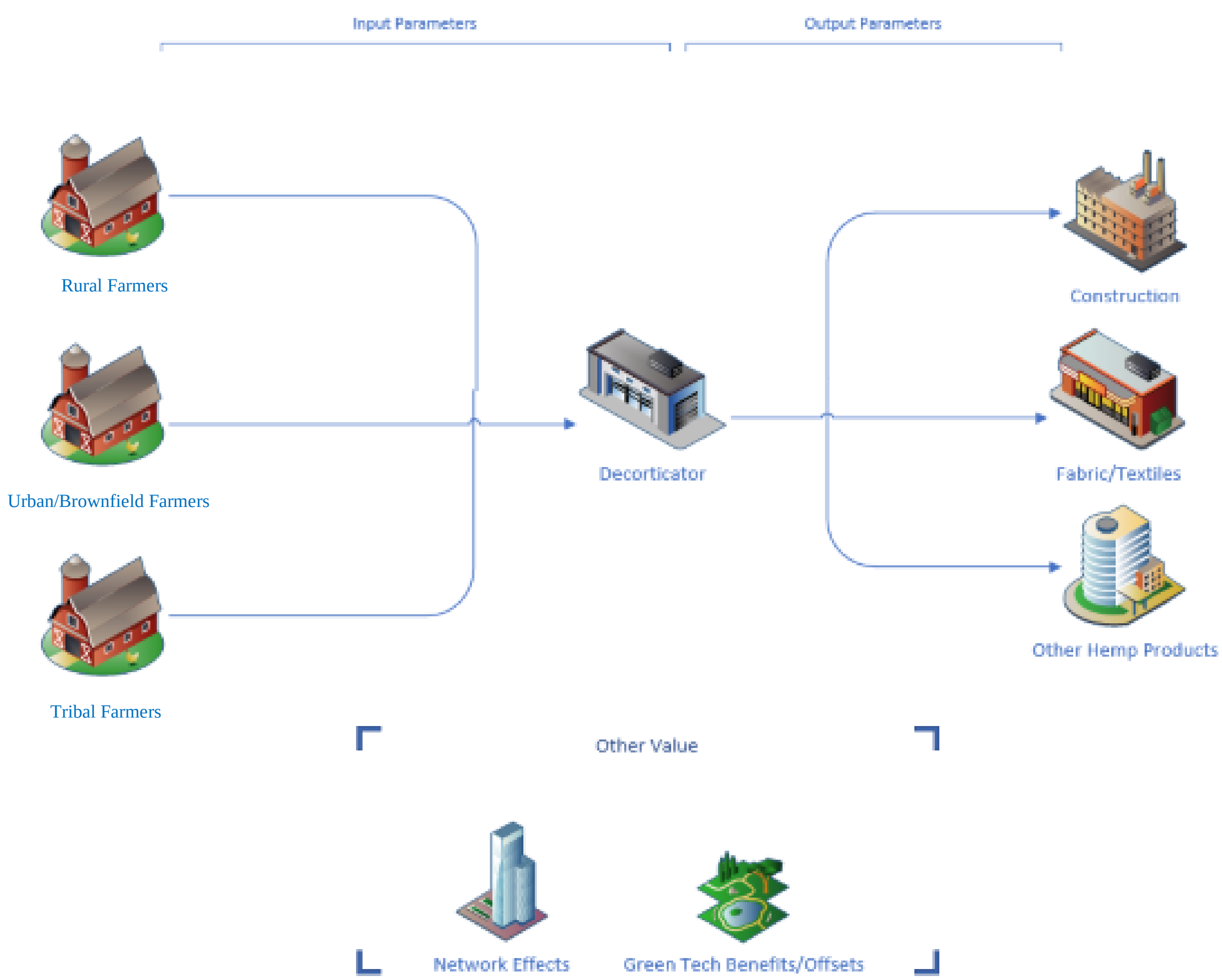


Figure 4: Economic Feasibility Analysis Centered Around a Decorticator

By examining different scenarios for key fixed and variable costs we can determine the feasibility to acquire and operate a particular decorticator. The table below lists the various input and output parameters of the scenario builder, which allows for adjustments to processing input and output quantities and their corresponding prices with respect to several potential decorticators. Some of these parameters are given based on the specifications of the manufacturer such as cost of equipment, square footage required for processing, kilowatt hours, processing capacity per hour, and minimum labor required.

Input Parameters		**Output Parameters**
Variable Costs **Raw material price** **Raw material quantity** Maintenance costs Electricity costs Labor quantity Labor costs Operating hrs/day **Days in operation** **Composition of raw material (Hurd/Bast)**	Fixed Costs Storage costs Equipment costs Training **Decorticator cost** Licensing cost • Rent of operational and storage space	**Price of hurd** **Price of bast** **Expected quantity of hurd** **Expected quantity of bast** Expected quantity of waste/non fiber Price of waste/non fiber material **Results** **Estimated revenue and profit** **Estimated years to payback**

Table 1: Input and Output Parameters for the Decorticator Analysis

We attempt to simplify decorticator selection using volume of raw material for processing as our input parameters and the corresponding potential operating profit and the estimated years to profitability or payback period as the key output metrics for this initial feasibility investigation. This approach parallels Pecenka et al. (2012) on identifying scenarios and conditions for economic feasibility of hemp fiber processing plants (Pecenka et al., 2012). To arrive at these figures, we estimated costs and revenues for each decorticator set up and assumed all annual operating profits are used to pay back the capital investment for each. In researching the costs and revenues we found other variables, some of which were out of scope but have meaningful impacts to the time to profitability or payback/breakeven period. An in depth exploration of these other areas that have potential to impact profitability can be found in a review of hemp fiber composites (Müssig et al., 2020). The relationship of these other variables is represented in the diagram below.

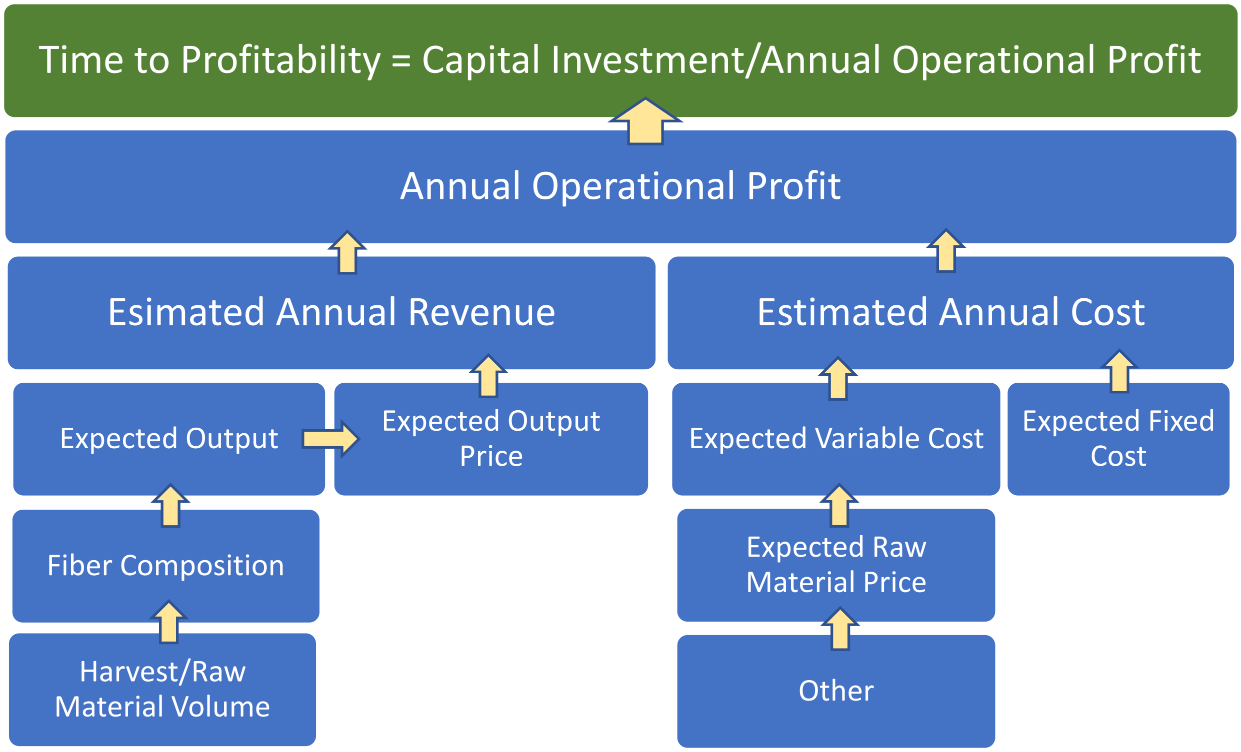


Figure 5: Calculation Flow Diagram

Using this as a framework, a model was constructed to adjust key components and demonstrate how sensitive a decorticator's payback or break-even time frame is to changes. Demonstrating how these different elements manifest in length of the payback period also highlight areas needing further investigation for a deeper economic feasibility analysis. This can also be expanded to account for subsidies, carbon credits and grants.

Controllable variables include harvest volume and the composition of fiber in the hemp harvest. Although the composition and quality of fiber in the hemp harvest are dependent on farmer skill and knowledge which are out of scope from the standpoint of the processor, we can attempt to estimate changes in revenues based on fiber content to demonstrate its impact to profitability. A qualitative difference that could not be modeled was regarding customization of decorticator output. Some decorticators have more options to customize output products for specific applications ensuring a more uniform and consistent product which is very desirable in construction, building materials, and other specialized technical uses. Other qualitative differences include portability which was another feature we were unable to model but may be a key factor in decorticator choice.

We considered four decorticators in our analysis for the economic feasibility of processing hemp; LaRoche, HempTrain, FiberTrack 660, Hurdmaster (Figure 6). Information about each decorticator's price, key features and capabilities are provided in Table 2 with a summary of key pros and cons for each in Table).

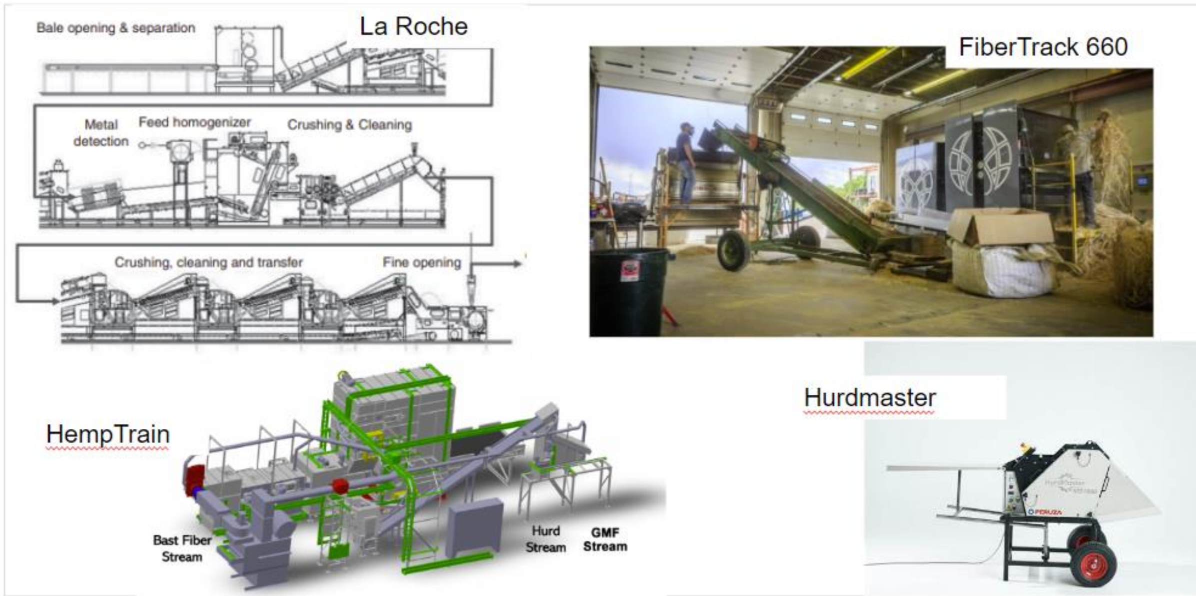


Figure 6: The decorticators used in the analysis

	La Roche	HempTrain	FiberTrack 660	Hurdmaster
Cost of Machinery	**$4.93 M**	**$3.9 – $3.95 M**	**$874.5 k**	**$13 k**
Processing Speed	**1.7-4 T/hr**	**1-2 T/hr**	**1-2 T/hr**	**.01-.05 T/hr**
Electricity in kWh	150	75.73	101.2	1.5
Product customization	Highest	High	Moderate - High	Lowest
Operational Area (sq. ft)	**25000**	**1500**	**500**	**25**
Portability	No	No	Yes	Yes
Waste produced	Minimal	Little to none	Little to none	Most
Import	New–Yes Europe Resale - No	Yes - Canada	No–built in the U.S.	Yes - Europe
Air Filtration/Dust Collection	Yes	Yes	Some	None
Retting Required[1]	**Yes**	**No**	**No**	**Yes**
Manual labor	Minimal	Minimal to moderate	Minimal to moderate	**Highest**

Table 2: Operational parameters and requirements for each decorticator.

[1] Retting starts the process to separate plat fibers by using the natural environment (water, bacteria) to start breaking down the plant.

Model	Pros	Cons
LaRoche	• Highly customizable fiber processing • Minimal waste • Processing capacity 2-3T/hr	• Requires large amount of sq. footage • Not portable • Cost • Import
HempTrain	• Customizable fiber processing • Minimal waste • Does not require hemp to be retted • Processes 1-2T/hr • Includes training	• Moderate square footage required • Not portable • Licensing fee(s) • Import
FiberTrack	• Customizable fiber processing • Minimal waste • Does not require hemp to be retted • Can be moved • Small footprint 1500 sq. ft (machine) • Upgradeable • Domestic shipping costs • Processes 1-2T/hr	• Training costs extra • Air filtration and dust collection not as extensive as competitors • May require additional customization
Hurdmaster	• Very compact • Portable • Limited fiber customization • Processing facility is not required • Most affordable • Low maintenance costs	• Fiber customization allows for 3 sizes of hurd. • Buyer preferences such as uniformity and color must be done manually which may increase labor costs. • Additional labor to sort and package product • Smallest processing capacity .05-.01T/hr. Can be made up with increased # decorticators • Import • Most potential for waste because small particle/ dust recapture is manual

Table 3: Pros and Cons for each Decorticator

3.2. Estimating input costs and output revenues

We attempt to simplify decorticator selection based on select input and output parameters. Input conditions are tied to the expected volume of hemp harvested for fiber and output conditions consider the quantity of expected output products. For this analysis, we assume that these conditions are reflected in the price of the raw material and the expected sale price and quantity of hurd, bast, and other material post decortication, and that all inputs and outputs are bought or sold at such rates to estimate the costs and revenues for each decorticator[2].

We begin with a given volume of hemp harvested for fiber which determine the quantities of output products for a decorticator which are bast, hurd, dust, and waste. Since the amount of fiber in the plant is dependent on the cultivar and growing conditions, it is important to know the general expected proportion of raw material that can be processed into hurd and bast that can be sold after decortication. The stalk is primarily where hemp fiber comes from and for fibrous varieties it can compose up to 70-75% of the plant (Bouloc, 2013; Găgeanu et al., 2020; University of Wisconsin Extension, 2019) with hurd composing the bulk of the stalk. Hemp that is not purposed for fiber typically have a much lower percentage of fiber contained in the stalk, Găgeanu et al noted that indigenous varieties of hemp can contain 10-12% fiber. Using expected proportions of bast, hurd, and other plant material for a particular or average fiber varietal we can estimate fiber processing revenues when combined with market prices for these products. Below are current price ranges for primary decorticator outputs bast and hurd from New Frontier Data, a hemp market analytics firm.

	Bast	**Hurd**	**Other/Dust**
$/lb.	$0.13/lb. - $1.00/lb.	$0.50/lb. - $0.75/lb.	--

Table 4: Parameters for Composition of Hemp

Combining the percentages of expected output with expected output prices and the capabilities of each decorticator, we can estimate expected revenue based on the amount of hemp that is or is expected to be harvested. For example, if the harvest is expected to yield 4 tons of hemp per acre, and the total hemp harvested is 200 acres, the total expected harvest should result in 800 tons of raw material. Assuming the entire fiber harvest is sold for processing, an estimate of output quantities can be derived using the expected proportions of bast, hurd, and other plant material for a specific cultivar or varietal. The resulting expected output is used to calculate the estimated expected revenue using market prices such as the ones above.

Input volume and raw material costs are based on prices for hemp grown in the open and utilized from the USDA's first hemp production report, the 2021 National Hemp Report. Dual purpose hemp was estimated by combining Oregon fiber price/lb. with the national price/lb. for grain. Table 5 presents the price per pound for floral, grain, and dual to provide contrast and assess the state of current hemp production from suppliers. Dual crop and fiber varieties can be processed by decorticators, whereas varietals used for grain and floral are not ideal for processing since they

[2] We also assume that qualitative parameters regarding the input and output product are held constant. Additionally, input prices are heavily influenced by producer (farmer) decisions and weather conditions while output prices will be influenced by buyer preferences for all products from the decorticator. Both are out of the control of fiber processing and currently out of scope for this analysis.

contain fewer proportions of fiber and the fiber from them can be of lower quality (Găgeanu et al., 2020; Müssig et al., 2020).

	OR prices	OR yield in lb/acre	Nat'l. price	Nat'l. yield in lb/acre	Highest price	Corresponding yield in lb/acre
Fiber	$0.38/lb (2021)	2,080	$1.50/lb	2620	$3.47/lb (NC)	6,280
Dual (Grain/Fiber)	N/A	N/A	$2.22	N/A	N/A	N/A
Grain	N/A	N/A	$1.84/lb	530	N/A	N/A
Floral	$106/lb	1,450	$39.60/lb	1,235	$503/lb (MA)	890

Table 5: Summary of current prices

Also included in decorticator costs are estimations of maintenance, labor, storage space, electricity, and rent for processing space based on each decorticator's capabilities. Estimates on these costs are derived using data available from the reference sources listed in Appendix 1. While this is not an extensive list of all cost and revenue variables included in the model, this presents the key variables that we felt would be most relevant for the reader.

3.3. Scenarios

We generate multiple scenarios based on the following parameters

1. Input quantities (lbs and acres)
2. Output prices (hurd and bast prices)
3. Composition of plant (% stalk)
4. Operational time (number of days the Decorticator will operate)

and compare the decorticator across

1. Minimum input quantities (and acres) for profitability (given input prices and output prices, operational time)
2. Time to profitability by output prices, input quantities/acres
3. Minimum break even annual operational time (given input prices and output prices, quantities/acres vary)

3.4. Results

We present figures of the Net Revenue by decorticator type under two different assumptions about prices for selling only hurd and both hurd and bast in Figure 7 and 8 below. The analysis shows that at low prices - products from hurd and bast is necessary to achieve financial feasibility. Based on parameters used FiberTrack660 provides the best financial return but it's important to note that the differences between decorticators is small relative to differences due to parameters (land area, yield per acre, prices etc.)

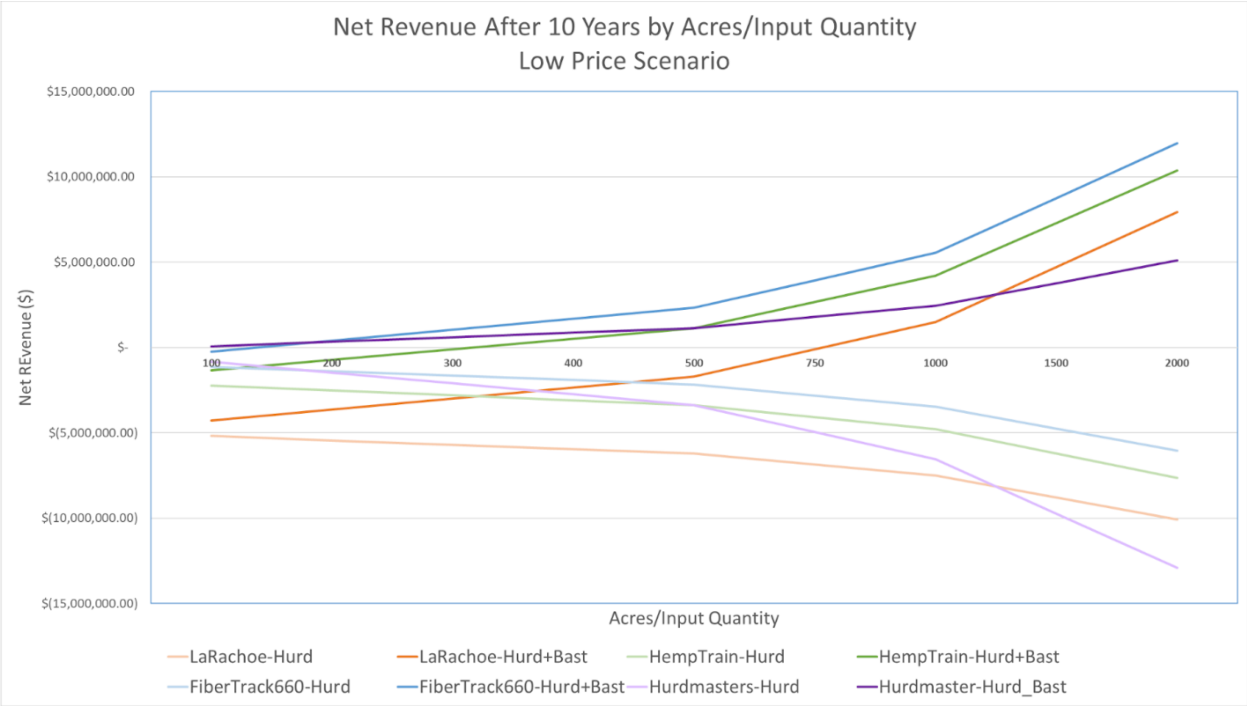


Figure 7: Net revenue by decorticator for low prices

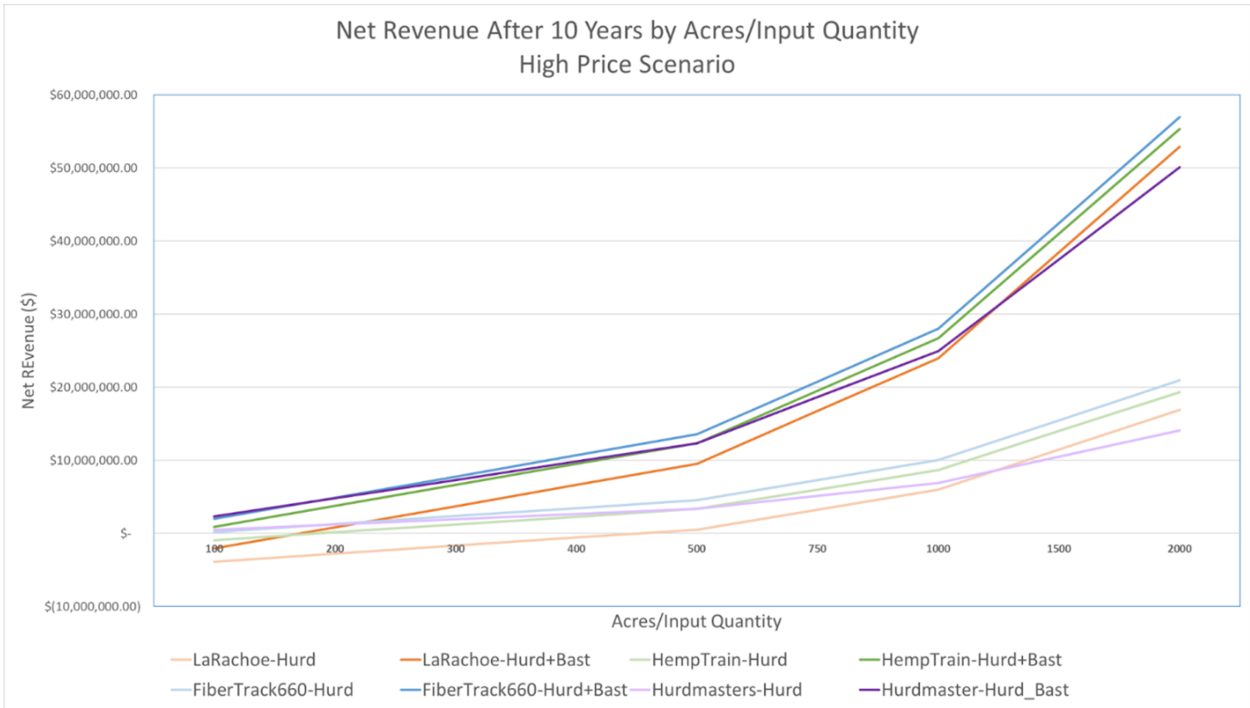


Figure 8: Net revenue by decorticator for high prices

We present figures of the Years to Profitability by decorticator type under two different assumptions about prices for selling only hurd and both hurd and bast in Figure 9 and 10 below. The analysis shows at 1000 tons of input (500 acres at a yield of 2 T/acre) all decorticators would be profitable within five years given high prices and selling hurd and bast. The results also show that if selling only bast, at high prices, profitability can be achieved within 4-9 years for all decorticator (for 1000 tons) and that at low prices processors would need to sell hurd and bast for profitability. Finally, the FiberTrack 600 has the fastest time to profitability

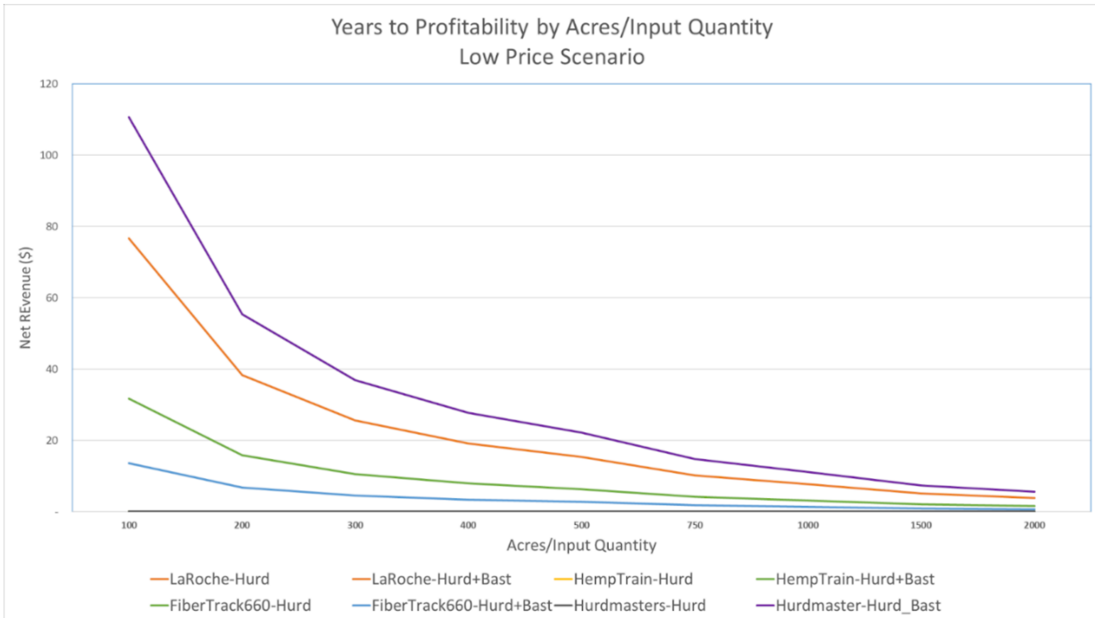


Figure 9: Years to profitability by decorticator for low prices

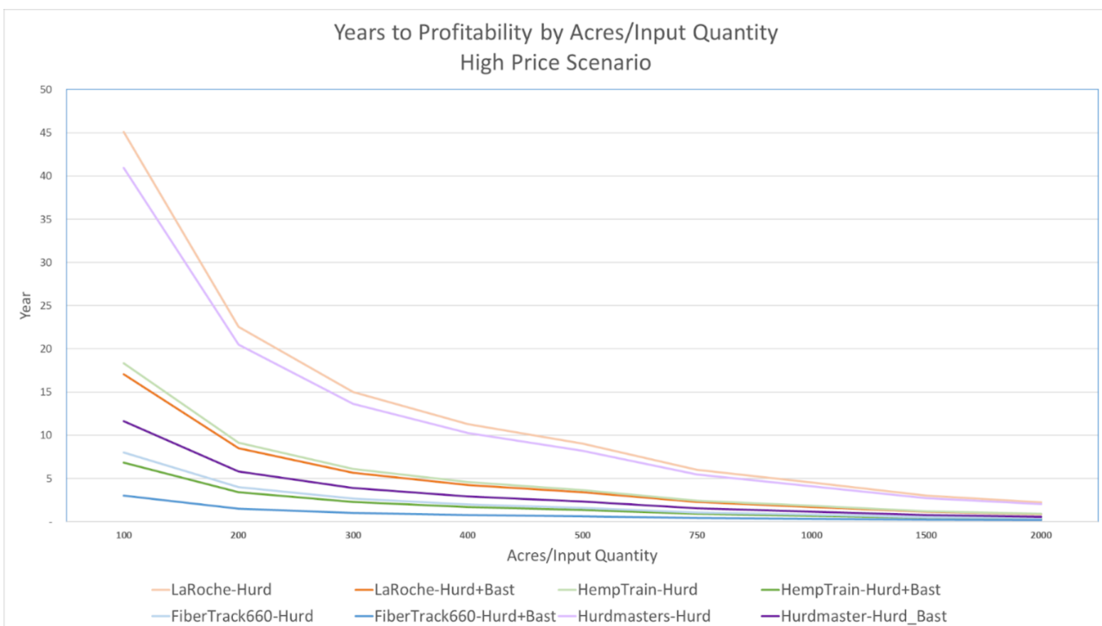


Figure 10: Years to profitability by decorticator for high prices

The key results for time to profitability and net revenue after 10 years for 1000 tons of inputs and 2000 tons of inputs for low and high prices scenarios are provided in Panels A, B and C in the Table below.

Panel A

Time to Profitability for 500 acres (1000 tons)					
	Low Price		High Price		
	Hurd	Hurd and Bast	Hurd	Hurd and Bast	Operating Time
La Roche	N/A	15 years	9 years	3.5 years	3 months/year
Hemptrain	N/A	6.3 years	3.5 years	1.5 years	5 months/year
FiberTrack-660	N/A	3 years	1.5 years	0.5 years	3 months/year
HurdMaster (15)	N/A	22 years	8 yesrs	2.5 years	4 months/year

Panel B

Net Revenue After 10 years for 500 acres (1000 tons)				
	Low Price		High Price	
	Hurd	Hurd and Bast	Hurd	Hurd and Bast
La Roche	-6.2 mil	-1.7 mil	0.5 mil	9.5 mil
Hemptrain	-3.3 mil	1.1 mil	3.3 mil	12.3 mil
FiberTrack-660	-2.1 mil	2.3 mil	4.5 mil	13.5 mil
HurdMaster (15)	-3.3 mil	1.1 mil	3.3 mil	12.3 mil

Panel C

Net Revenue After 10 years for 1000 acres (2000 tons)				
	Low Price		High Price	
	Hurd	Hurd and Bast	Hurd	Hurd and Bast
La Roche	-7.4 mil	1.5 mil	6 mil	24 mil
Hemptrain	-4.7 mil	4.2 mil	8 mil	26 mil
FiberTrack-660	-3.5 mil	5.5 mil	10 mil	28 mil
HurdMaster (15)	-6.5mil	2.5 mil	7 mil	25 mil

Table 6: Summary of Scenario Analysis

Overall, across all the simulations we have conducted we find that processing industrial hemp is likely to be profitable, the FiberTrack 660 has the fastest time to profitability/highest net revenue. But it's important to note that the economic feasibility is more sensitive to prices, cost, and other parameters than choice of decorticator. It is also important to note that the results above rests on some key assumptions and caveats discussed in Appendix 1.

4. Industrial hemp's potential as a carbon sink solution

4.1. Introduction

In this section we calculate the carbon footprint of industrial hemp and hemp-lime insulation. Based on the parameters compiled through literature review (Vosper, Gandolphy, 2016; B: Jankauskienė et al, 2015, Crônier et al, 2005; Van der Werf, 2004, Baral et al., 2020, IP and Miller, 2022), we estimate 1.37 to 1.6 mT of CO2 metric tons (mT) of carbon dioxide is sequestered from producing 1 mT of industrial hemp. Assuming a conservative estimate of 2.3 mT of industrial hemp harvested per hectare (USDA, 2021), 3.151-3.68 mT of carbon dioxide is expected to be sequestered per hectare (ha) of industrial hemp cultivation.

This analysis was extended further to explore the carbon footprint of hemp-lime insulation, a buzz-worthy sustainable construction material made from hemp hurds, lime binder, and water. We estimate that 1 m^2 of wall insulated with hemp lime would result in approximately 10 kg of CO2 sequestered or 6.24 kg of CO2 emitted based on the various factors of the lifecycle previously discussed. In contrast, a 1 m^2 section of wall insulated with fiberglass is expected to result in 47.25 kg of CO2e. Although this estimate was calculated with several limitations, the results indicate using hemp-lime instead of fiberglass insulation will result in less CO2 emissions and ultimately reduce insulation's contribution to global warming.

These results affirm that hemp-based construction materials would have a positive environmental impact in terms of CO2 emissions, and could contribute to Oregon's emissions reduction goals. Oregon's Climate Action Plan includes plans to increase sequestration of natural and working lands and promote green building construction. Based on the research and analysis presented below, hemp-based industrial materials like hemp-lime insulation are a viable carbon sink solution and a sustainable alternative to traditional insulation materials. Further, emerging hemp-lime products are capable of supporting structural loads which would eliminate traditional wood framing – potentially contributing to additional carbon benefits for a hemp-lime structure.

4.2. Assumptions

The assumptions used for the following calculations are intended to represent the area of interest for this project, which is the state of Oregon. Calculations are primarily conducted with metric units including metric tons (mT), kilograms (kg), and hectares (ha).

- **Yield ($\boldsymbol{M_{HempHa}}$)**

  The calculation assumes a yield of 2.3 mT dry hemp per hectare (ha) which was the average harvest of fibrous hemp last year in Oregon (USDA, 2022). The harvestable yield is expected to vary depending on the environmental conditions, longitude, agricultural practices, and genotype. The 2.3 mT/ha is a conservative estimate given other genotypes have been known to produce as much as 12.32 mT/ha (Vandepitte et al., 2020) and Canada reported that 8.2

mT/ha is the expected harvest for fibrous varieties of industrial hemp (Alberta Agricultural Department, 2014). More detail on harvestable yield estimates can be found in Table 1A and 1B in Appendix 2.

- **Electricity (EF_{Pow})**
  Hydropower is the primary energy source in the state of Oregon (ODE), so any electricity used throughout the lifecycle is assumed to be generated by hydropower. Hydropower is expected to result in 0.000024 mT of carbon dioxide per kilowatt-hour (kWh) (IHA). More detail on emissions factors (EF) can be found in Table 1C in Appendix 2.

- **Emissions sequestered through photosynthesis (ES_{hemp})**
  All carbon dioxide sequestered through the process of photosynthesis is used to calculate the carbon footprint of 1 mT of industrial hemp, which ultimately is used to estimate the carbon footprint of hemp-lime insulation. If the scope of the analysis widened to estimate the carbon footprint of other industrial materials produced from hemp, the sequestration would need to be allocated appropriately based on what component of hemp was used to produce the material to prevent double counting carbon sequestered.

- **Emissions from useful distance traveled (ES_{hemp})**
  Emissions from transportation of raw materials is estimated under the assumption the class 8 vehicle is driven on a paved, undamaged highway (Baral et al, 2020). Considering the use of hybrid and electric vehicles while completing a life cycle assessment is increasingly important as infrastructure to support the adoption of electric vehicles (EVs) continues to grow. Including this in the analysis was relevant considering the area of interest is the state of Oregon. In 2021, Portland General Electric (PGE) and Daimler Trucks North America (DTNA) opened the 'Electric Island', an EV charging site for medium to heavy-weight trucks (Ligouri, 2021). PGE is part of the West Coast Clean Transit Corridor Initiative, a collaborative effort between 16 utility companies to establish EV charging stations for medium-heavy duty vehicles on I-5 from San Diego to British Columbia (HDR).

4.3. Methods

The carbon footprint of industrial hemp and hemp-lime insulation was estimated by Life Cycle Assessment (LCA) methodology, limited to the CO2 emissions expected to occur during the production of the raw materials, production of the commercial material, and installation. A literature review was completed to identify the parameter values included in the CO2 calculations and emissions factors were collected from various sources (U.S. EPA 2018, U.S. EPA 2020, EIA 2020, IHA, Barat et al. 2020). Since emissions will vary based on production decisions, a 'best' and 'worst case' scenario is provided to articulate the range of CO2 emissions that can be expected to occur.

Scope of Life Cycle Assessment for Carbon Impacts

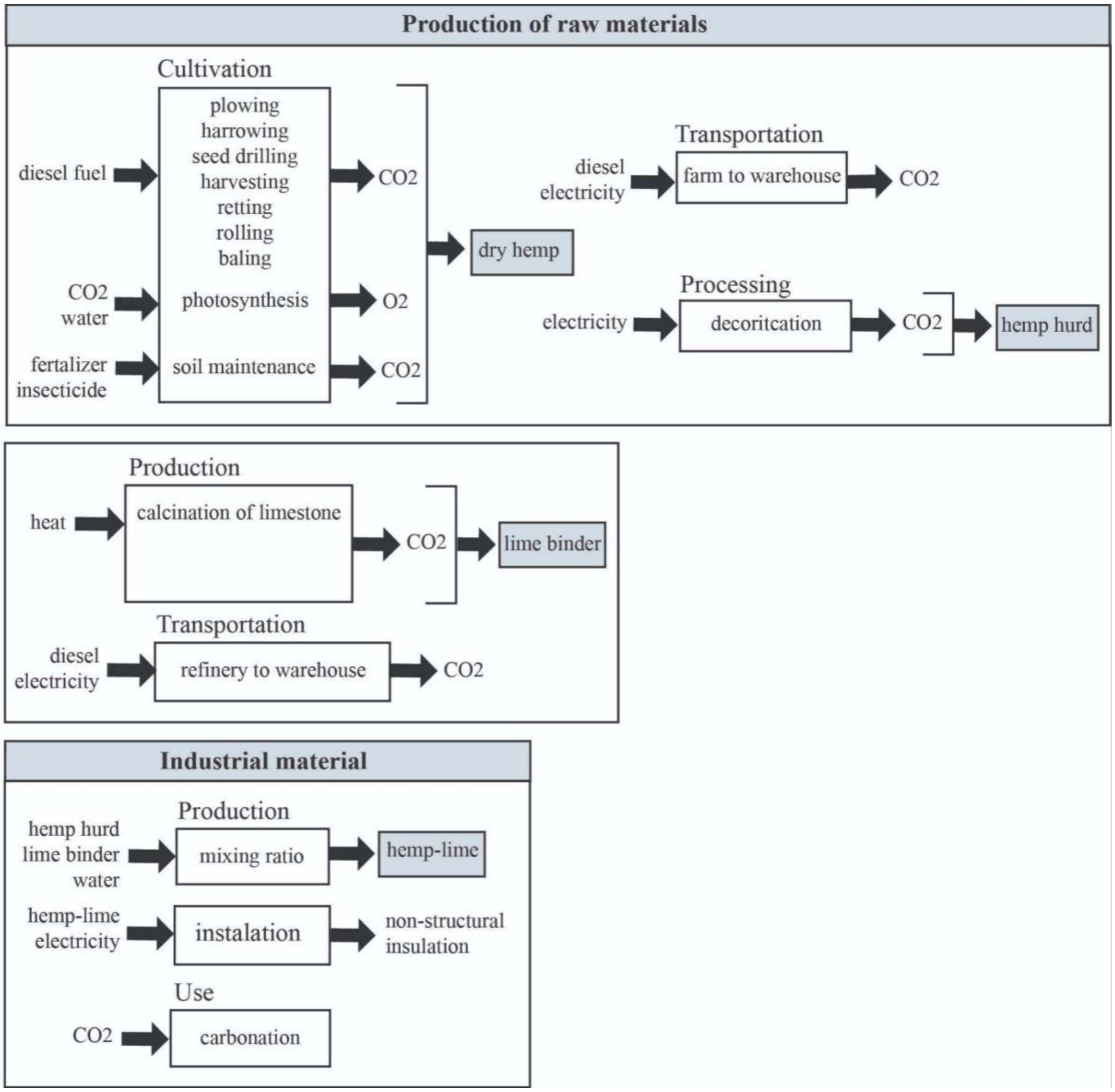


Figure 11: Scope of life cycle assessment for carbon impacts for hemp hurd and hemp lime

4.4. Results

Hemp sequesters carbon dioxide from the atmosphere through photosynthesis. The CO2 sequestered by industrial hemp can be calculated by determining the chemical composition of the plant as modeled in Equation (1) in Appendix 2 (Vosper). Based on the chemical composition of the hemp varieties considered below, cultivation of 1 mT of industrial hemp is expected to sequester 1.37 to 1.6 mT of CO2.

Variety	Class	Lignin (%)	Cellulose (%)	Hemicellulose (%)	ES_{hemp}
Carmagnola	Fiber	0.44	0.25	0.23	1.50
USO 31	Dual-purpose	0.81	0.06	0.12	1.60
Fedora 17	Dual-purpose	0.75	0.07	0.01	1.37

(Gandolphy, 2016; B: Jankauskienė et al, 2015, Crônier et al, 2005)

Table 7: Carbon Sequestration by Variety of Hemp

The fertilizer use and soil management impacts carbon sequestration from growing hemp and the fertilizer recommendations vary depending on situation-specific factors like the soil profile, preceding crop, and farming methods. For soil with optimum levels of phosphorus and potassium, The Agricultural Analytical Services Lab at Penn State University recommends 150 lb. of nitrogen, 30 lb. phosphate, and 20 lb. of potash for the cultivation of industrial hemp (Roth et Al 2018).

For this analysis, four 'soil maintenance' scenarios were used to estimate the emissions from managing soil fertility (Hayo M.G. Van Der Werf, 2004). Using the parameters outlined in Table 2 in Appendix 2 the emissions from soil management were estimated using Equation (2) in Appendix 2. Considering 'good agricultural practice' which consists of applying a traditional nitrogen-based fertilizer to a tilled seedbed, soil maintenance is expected to emit 2.3 mT of CO2e per ha (Van Der Werf, 2004) and based on the assumption of 2.3 mT of hemp is harvested per ha, 1.013 mT of CO2e is emitted from soil management per ton of industrial hemp cultivated.

Sustainable soil management like the use of pig slurry, reduced tillage, and reduced leaching is expected to reduce CO2e emissions (Van Der Werf, 2004). Pig slurry is an organic fertilizer that has the lowest carbon footprint of all soil scenarios reviewed by Hayo M.G. Van Der Werf. The use of pig slurry is expected to emit 1.77 mT of CO2 per ha or 0.77 mT of CO2 per mT of industrial hemp, but it is unclear whether pig slurry is an accessible and acceptable alternative for farmers in Oregon. A southern Oregon company, All Natural Farms, advertises all-natural pig manure for $10 per yard but this was the only seller of pig slurry we've identified in Oregon. Although pig slurry is expected to have the lowest carbon footprint, it was estimated to have a higher eco-toxicity and acidification effect than traditional fertilizer. These impacts are beyond the scope of this analysis but are important to note in consideration of the overall environmental costs and benefits of using pig slurry.

Farm machinery is required for preparation, planting, and harvesting industrial hemp crops. The emissions from farm machinery are expected to vary depending on the fuel efficiency of the equipment, farming practices, and environmental conditions. IP and Miller (2012) estimates 65.9 liters of diesel (17.41gallons) is required to cultivate 1 ha of industrial hemp. This estimate includes the farm equipment used for plowing, bailing, seed drilling, rolling, harvesting, retting, and bailing (Table 3) in Appendix 2. The emissions from farm machinery per ton of hemp can be calculated using fuel consumption per ha (IP and Miller, 2012), mT of hemp per ha (USDA, 2021), and the emissions factor for diesel fuel as modeled in Equation (3) in Appendix 2. Based on these parameters, farm machinery is expected to result in 0.18 mT CO2 per ha or 0.08 mT CO2 per mT of industrial hemp cultivated.

After the hemp is baled, it will be transported to a processing facility. The emissions from transportation are expected to vary based on the fuel efficiency, capacity of the vehicle, and the distance traveled. A study by Baral et. al (2020) examined the environmental and economic impacts of using diesel, fuel cell hybrid, or electric class 8 vehicles to transport biomass. The fuel efficiency and capacity parameters of three class 8 transportation vehicles (Table 4) in Appendix 2 were used to estimate the emissions from the useful distance traveled as modeled in Equation (4) in Appendix 2. The results are provided in Table 5 of Appendix 2. At the bare minimum, using a fully electric class 8 vehicle for a useful distance of 50 miles is estimated to attribute 0.0000069 mT of CO2 per mT of hemp transported using the full capacity of the vehicles. The maximum considered for this analysis was 400 miles useful distance using a conventional class 8 vehicle which is estimated to emit 0.061 mT of CO2 per mT of hemp.

4.5. Hemp Hurd

Once at the processing facility, the dry hemp will be processed using a decorticator machine. The decorticator separates the bast fiber from the hurd, with some machines offering customization and additional filtering mechanisms. The energy required to run the FiberTrack 660, HempTrain HT-UF, and HurdMaster Micro (Table 6) in Appendix 2 was considered for the processing-related emissions modeled in Equation (5) in Appendix 2. The HurdMaster Micro is expected to have the lowest carbon emissions of 0.0009 mT of CO2 per mT of hemp hurd, but it’s also the least efficient machine only yielding 0.03 mT of hurd per hour. The FiberTrack 660 had the highest carbon footprint of the machines considered with an estimated 0.004 mT of CO2 per mT of hemp hurd, however, this processor is much more efficient, producing approximately 1 mT of hemp hurd per hour. Given the analysis of the three decorticators, we observe a trade-off between efficiency and emissions, but the high emissions of FiberTrack 660 are still low compared to from soil management and transportation.

Emissions of producing 1 ton of hemp hurd

$$\boldsymbol{E_{hurd} = HempES_i + E_{SoilTon} + E_{FarmMach} + VehE_i + DecE_i}$$

Where:

$HempES_i$ is the CO_2 sequestered through photosynthesis per mT of hemp variety i
$\boldsymbol{E_{SoilTon}}$ is the estimated $\boldsymbol{CO_2}$ emitted per mT of fibrous hemp grown
$\boldsymbol{E_{FarmMach}}$ is the estimate of $\boldsymbol{CO_2}$ emitted by the farm machinery used per mT of hemp
$VehE_i$ is the CO_2 emitted during useful distance traveled by vehicle i
$\boldsymbol{DecE_i}$ is the estimated $\boldsymbol{CO_2}$ from producing 1 mT of hemp hurd with decorticator i

	'Best Case' Emissions		'Worst Case' Emissions	
Emissions sequestered	USO 31	-1.6	Fedora 17	-1.37
Farm equipment emissions	-	0.076	-	0.076
Soil maintenance emissions	Pig slurry	0.76	Good agricultural practice	1.01
Transportation emissions	Fully electric 50 mi	0.0000069	Conventional 400 mi	0.061
Processing emissions	Hurdmaster micro	0.0009	FiberTrack 660	0.004
	Total Emissions	-0.763	Total Emissions	-0.219

Table 8: Carbon Emissions for Producing Hemp Hurd

Given the assumptions for cultivation, transportation, and processing considered above, we conclude fibrous varieties of hemp are a viable carbon sink solution. Production of one ton of hemp hurd is expected to sequester between 0.219 and 0.763 mT of CO2 depending on the parameters of a given scenario.

Soil maintenance and farm equipment make up the majority of emissions and it would be advantageous to explore strategies that could reduce emissions within these stages of the lifecycle. Although it's beyond the scope of this analysis some possibilities are, growing hemp as a rotational crop is a strategy that should be explored further to reduce the requirement to apply nitrogen based fertilizer that is typically required, thus reducing carbon footprint. Increasing the harvestable yield per ha would also decrease the marginal emissions (mT CO2 per mT of dry hemp) and although electric vehicle (EV) transport may not currently be realistic, the use of EV vehicles is another strategy to reduce the CO2 emissions.

4.6. Hemp-lime insulation

In April 2022, the International Code Council (ICC) approved Proposal RB316-22 which is the first official step towards adding hemp-lime to the International Residential Code (USHBA). The proposal defines the requirements and limitations for use of hemp-lime insulation in U.S. residential buildings.

Hemp-lime or 'hempcrete' is a non-structural insulation material used between or around structural or non-structural wall framing. Various ratios of ground hemp hurd, lime-based binder, and water are used depending on the requirements of a given project. After the hempcrete mixture is sprayed into the framework and dries, a lime-based plaster is applied to the interior and exterior surfaces. Typically, a sand-lime coating is used for the outdoor side and a hemp-lime coating is used for the indoor side; both are applied by hand with a trowel. The result is a breathable wall assembly that improves indoor air quality and regulates humidity.

Cross-section of the hemp-lime insulated wall

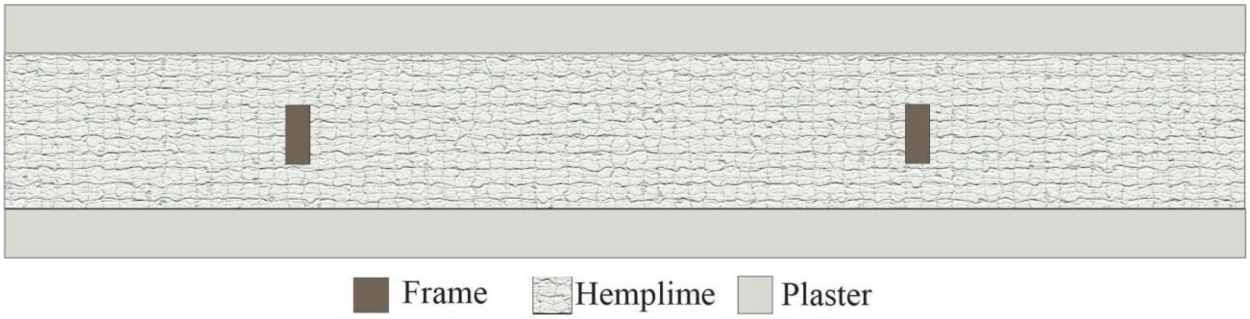


Figure 12: Hemp-lime Wall Design

The emissions from producing lime binder are expected to vary based on the type of binder and the extraction processes used to obtain the binder material. Hydrated lime, hydraulic lime and dolomite lime have been used to produce hemp-lime. Clay has also been used to produce hemp-clay building material (Fernea, 2019), but the scope of this analysis is limited to hemp-lime. Hydrated lime can prolong the setting time, so hydraulic and pozzolanic binders are often added to speed up the drying process (Arehart et al., 2020). Pretot et. Al (2014) estimated that 0.778 mT of CO2 is emitted from producing 1 mT of quick lime composed of 75% hydrated lime, 15% hydraulic binder, and 10% pozzolanic binder; 0.594 mT of the emissions result from calcination of limestone and 0.178 mT from the production of the hydraulic binder. This estimate was used for our calculation, but Equation (6) in Appendix 2 could be useful to extend the emissions calculation for a lime binder with a different composition.

Based on the requirements outlined in the IRC proposal, we expect the hemp:binder ratio to be no less than 1:1 and no more than 1:2 by weight. Assuming the hemp hurd production is carbon negative (as demonstrated previously), the 1:1 hemp: lime ratio would result in a lower carbon footprint from incorporating more hemp hurd than the 1:2 ratio. Although this parameter does impact the carbon footprint of the material, we acknowledge the performance and durability requirements should be prioritized when determining the hemp: lime ratio rather than the expected emission benefits. Using Equation (7) in Appendix 2 and the best and worst-case emissions calculated for hemp hurd, we estimate that 1 mT hemp-lime produced with a 1:1 ratio will emit 0.0085 mT of CO2, and production using a 1:2 ratio is expected to emit 0.44 mT of CO2.

Hemp-lime insulation can be installed using masonry, form infill, or a spray-in method. The emissions expected from installation were calculated using energy parameters collected from IP and Miller (2012) (Table 7) and emission factor for electricity as modeled in Equation (8) in

Appendix 2. Because the production of masonry units is expected to incur more secondary impacts (labor, storage, etc.), this calculation is limited to spray in and formwork. We estimate the installation to have minimal impact on the carbon footprint, formwork has slightly lower emissions of 0.000029 mT of CO2 per mT of hemp-lime, while the spray-in method is expected to emit 0.000069 mT of CO2 per mT of hemp-lime.

After the hemp-lime is installed and dried, sand-lime and hemp-lime coatings are applied, eliminating the requirement to use a gypsum board. The hemp-lime insulation and lime-based coatings will continue to absorb carbon dioxide during the 'use phase' of the material. Through the process of carbonation, the lime-based materials absorb CO2 while releasing H2O. By the expected end-of-life of the functional unit (100 years), all binders will be 'carbonated' which Pretot et. al (2014) estimated to result in 0.46 tons of CO2 per ton of hemp-lime. Using hydrated lime instead of dolomitic lime resulted in an 8.2% higher uptake of CO2 during the use phase (Arrigoni et. Al), but as mentioned before, hydrated lime can prolong drying time.

We calculate the emissions of producing 1 ton of hemp-lime insulation as

$$\boldsymbol{E_{HempLime} = E_{ratio} + E_{instal} + ES_{lime}}$$

Where:

E_{ratio} is the estimated emissions for a hemp:lime ratio i
E_{instal} is the estimate emissions for installation method i
$\boldsymbol{ES_{lime}}$ is the estimated emissions sequestered through carbonation of lime present in hemp:lime ratio i

	Min Emissions		Max Emissions	
Hemp hurd emissions (1 T	Best case	-0.763	Worse case	-0.219
Lime binder emissions (1 T)	-	0.78	-	0.78
Hemp-lime emissions (1 T) ratio	1:1	0.0085	1:2	0.44
Installation emissions	Form infill	0.000029	Spray-in	0.000069
Carbonation of lime binder	1:1	-0.23	1:2	-0.3
	Total Emissions	-0.22	Total Emissions	0.14

Table 9: Carbon Emissions for Hemp Lime Insulation

Given the assumptions for production of raw materials, production of commercial material, installation of commercial material, and limited consideration of the use phase considered above, we conclude hemp-lime insulation can be carbon positive or carbon negative dependent on decisions made throughout the product's life cycle. Production of one ton of hemp-lime is expected to sequester as much as 0.22 tons of CO_2 per ton of hemp-lime or emit up to 0.14 tons of CO_2 per ton of hemp lime.

4.7. Hemp-lime insulated wall

Hemp-lime has different insulative properties and densities than traditional insulation materials like fiberglass, rockwool, and polyurethane foams. Hemp-lime has a high-density, online sources estimate hemp-lime can range from 94 to 330 kg/m^3 (Hemp Tech Global; Sutton et. al). In contrast, unbonded loose infill fiberglass insulation has a much lower density. The brand considered for the following analysis, Owens Corning, offers insulation products with a density between 20 kg/m^3 and 28 kg/m^3 depending on the R-value. Because of these differences, it's necessary to evaluate the embodied carbon in terms of the insulation required per application or functional unit. With that being said, the scope of this section of the analysis is limited to embodied carbon of a 1 m^2 section of wall insulated with either hemp-lime or unbonded loosefill fiberglass and was completed with the following limitations.

- **CO2 vs. CO2e**
  All emissions calculations completed for the raw materials of hemp-lime (hemp hurd and lime binder) were limited to CO_2, except 'Soil Maintenance' which estimated emissions in terms of CO_2e. Although we expect the 'Soil Maintenance' is likely to result in the highest emissions of other GHG considered CO_2e, like methane, we acknowledge that other GHG emissions that can attribute to CO_2e are likely to occur in other phases of the lifecycle. Because CO_2e is not accounted for within other phases of the analysis, we cannot offer a true apples-to-apples comparison between the estimates for hemp-lime and fiberglass insulated walls since the embodied emissions of the fiberglass insulated wall are measured in terms of CO_2e. With that being said, the difference between the embodied carbon of the two materials is large and the unaccounted CO_2e emissions is not expected to change the final conclusion that hemp-lime is superior to fiberglass in terms of embodied carbon.

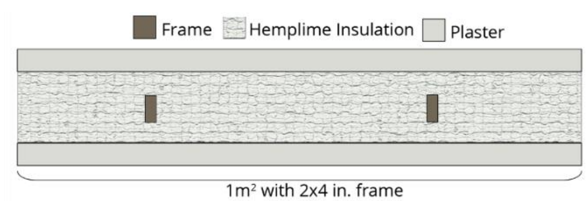
- **Hemp-lime and sand-lime plaster**
  The following analysis only accounts for the embodied carbon of the interior hemp-lime plaster and doesn't account for the exterior sand-lime plaster. The embodied carbon of hemp lime plaster is estimated based on the assumption it follows the same lifecycle as hemp-lime insulation. This is an oversimplification and future research should refine this rough estimate. In addition, hemp-lime insulated walls are expected to last 100 years and plaster is expected to need maintenance 2-3 times throughout the lifespan (Pretot et. Al) which should also be considered.

- **Use Phase**
  The life cycle analysis of a building considers the construction, use, and end-of-life stages of development. Several studies indicate that the use or operational phase is often the most

harmful to the environment (Pretot et. al). Installing hemp-lime insulation to maximize thermal resistance could decrease energy consumption, thus decreasing the carbon emissions associated with temperature regulation of buildings. There are several studies that use life cycle analysis to examine the impact on the embodied energy of a building (Aversa, 2021; Moujalled, 2018; Tettey, 2014). This analysis is beyond the scope of this paper, but it is clearly an important factor to understand environmental impacts and feasibility of using hemp-lime to insulate residential buildings.

- **Lifecycle Analysis (LCA) of hemp-lime vs. fiberglass**
  The LCA of hemp-lime was completed by the student intern who conducted a literature review of existing research and completed estimates by means of manual calculation. The LCA completed for fiberglass insulation products was completed by UL Environment using ecoinvent 3.4 and Simapro 8.5.2.0 software packages that are often used to conduct LCA and produce a certified Environmental Product Declaration (EPD). Because the LCA were completed using different methods the results should not be interpreted as a direct comparison. Instead, the results should be considered a benchmark for the embodied carbon of each insulation material. Conducting LCA with a firm that is able to provide a certified EPD is recommended.

Hemp-lime Insulated Wall



Fiberglass Insulated Wall

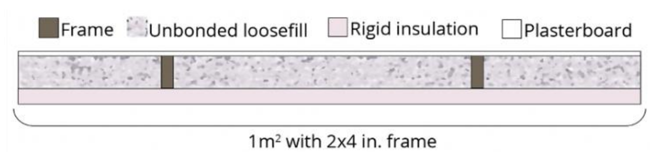


Figure 13: Comparison of Hemp-lime and Fiberglass Insulated Walls

A hemp-lime insulated wall is composed of hemp-lime insulation and an interior hemp-lime plaster and exterior sand-lime plaster. Because the hemp-lime infill shall be not less than 3 inches (76 mm) thick between the face of framing and finish (IRC Proposal AY103.3.4), there is no need to install rigid insulation. Rigid insulation is installed when a wall is insulated with loose infill fiberglass insulation to prevent thermal bridging from structural framing which ultimately results in loss of heat. The use of plasterboard is also not necessary because of the hemp-lime plaster applied to the interior face of the wall.

For this analysis, it's assumed that the fiberglass insulated wall is composed of unbonded loosefill fiberglass insulation, XPS rigid insulation, and gypsum plasterboard. Referencing the Environmental Product Declarations (EPD), the GWP for the two Owens Corning products, FOAMULAR® 150 XPS Insulation and PROPINK® L77 PINK® Fiberglas™ is provided in

Table 10. Both EPDs were completed for 1 at RSI = 1 by UL Environmental according to ISO 14025, EN15804, and ISO 21930:2017. See equation 9 and 10 in Appendix 2 for details of the calculations. Production of 1 sheet of Type A plasterboard is expected to result in 12 kg of CO2e emissions (Marsh, 2008) and only 0.34 of the sheet would be used for 1 meter squared wall. The traditional insulation material considered for this analysis was limited to one scenario. For more comprehensive comparison, we suggest reviewing "Embodied energy and carbon of building insulating materials: A critical review" by Graziechi et. Al (2021) which considers 156 EPDs of building panels made from various types of insulation material.

4.8. Emissions of insulating a 1 m^2 section of wall

The International Energy Conservation Code (IECC) is a set of standards that establish codes that must be followed to achieve energy-efficiency for residential construction within different regions of the United States. The minimum R-values required for ceilings, walls, and floors within different climatic zones are outlined by the IECC.

The R-value for the wall is the sum of the r-value of the 'cavity' and 'sheathing' insulation (ICC, 2018). The entire state of Oregon is within Climatic Zone 5 according to the IECC, so the minimum R-value for a wood-framed wall should be 20 (ICC, 2018). For our calculation, we assume the sheathing insulation has an R-value of 5 and the cavity insulation has an R-value of 15 to achieve the minimum requirement.

Hemp-lime insulated wall

	Product type	R-value	Min Emissions (kg of CO2)	Max Emissions (kg of CO2)
Sheathing	Hemp-lime plaster	5	-2.46	1.57
Cavity	Hemp-lime	15	-7.34	4.67

Fiberglass insulated Wall

	Product Type	Product	R-value	GWP (kg CO2e)
Sheathing	Rigid Insulation	FOAMULAR® 150 XPS Insulation	5	39.57
Cavity	Unbonded Loosefill	PROPINK® L77 PINK® Fiberglas™	15	3.64
NA	Plasterboard	Gypsum wallboard	-	4.04

Table 10: Comparison of hemp and fiberglass insulated walls

We estimate that 1 m^2 of wall insulated with hemp lime would result in approximately 10 kg of CO2 sequestered or 6.24 kg of CO2 emitted based on the various factors of the lifecycle previously discussed. In contrast, a 1 m^2 section of wall insulated with fiberglass is expected to result in 47.25 kg of CO2e. Although this estimate was calculated with several limitations, the results indicate using hemp-lime instead of fiberglass insulation will result in less CO2 emissions and ultimately reduce insulation's contribution to global warming.

Critics have argued that although embodied carbon of bio-based materials like hemp-lime are negative or lower than traditional materials, carbon stored within the biomass is released back into the atmosphere during disposal (Grazieschi, 2021). The end-of-life stage is worth mentioning because it is critical to consider when discussing embodied carbon of hemp-lime insulation. At the end of its useful life, the insulation could be taken to a landfill or incinerated. Landfilling bio-based materials has been pointed to as the best option to reduce CO2 emissions during the end-of-life stage (Norton, 2008), the decay of the material in a landfill is expected to be slow and would eliminate the emissions that would occur if the product was incinerated. At the same time anaerobic digestion in landfills can generate methane therefore the end of life stages should be evaluated further.

5. Industrial hemp's potential to remediate brownfields

5.1. Introduction

This section explores the potential of growing industrial hemp in brownfields. A brownfield is a property where the use of the land is complicated by potential or actual environmental contamination of the soil (DEQ, 2022). Mining and mill sites, agricultural land, landfills, abandoned gas stations, auto shops, and dry cleaners are all common sources of soil contamination.

Effectively managing the restoration of brownfields can be complicated and costly, but there are significant economic, environmental, and social benefits of restoring brownfields. Because of this, public entities like the DEQ and EPA are often involved in the restoration of brownfields providing financial and technical assistance (U.S. EPA, 2022). The U.S. EPA estimated that last year, on average $20.43 was leveraged for every $1 spent on brownfield assessment and clean-up (EPA, 2021). This demonstrates the significant economic growth that can be expected from the development of revitalized brownfields. In a nationwide assessment conducted in 2020, Portland, OR was identified as a metropolitan city with a high density of brownfields and a high capacity for redevelopment (ICF and Renaissance Planning, 2020). Using the DEQ Environmental Contamination Site Identifier Databases (ECSI), we estimate Oregon has 176 active brownfield sites (Appendix 3: Figure 1) and 46 of these are in Multnomah County (Appendix 3: Figure 2).

Brownfield restoration offers positive environmental benefits beyond soil remediation. In a report prepared for the U.S. EPA Office of Brownfields and Land Revitalization, ICF and Renaissance Planning used scenario analysis to explore how brownfield revitalization could impact housing, employment, and transportation in metropolitan areas. The results indicate that brownfield redevelopment can reduce vehicle-related emissions, which has also been highlighted in a report published by Portland's DEQ (Maul 2012). The development of revitalized brownfields can also contribute to social equity and opportunity within communities. Portland's Brownfield Program has restored 78 sites since 1988, developing 110 acres into parks, community gardens, non-profits, small businesses, and affordable housing (Maul 2012).

Brownfield Redevelopment

Brownfields must be remediated before they can be redeveloped. Remediation consists of the removal of contaminants of concern (COC) from the soil using physical, chemical, or biological technologies. Chemical and physical technologies are expensive, have negative secondary impacts, and are often ineffective when the concentration of contamination is low (Yan et al., 2020).

Phytoremediation is a biological technology that utilizes vegetation to remove, contain, or reduce contaminants from the soil (FRTR). In general, this is an ideal remediation technology for restoration projects that are not time-sensitive and for sites with low contaminant concentrations.

Phytoremediation is environmentally friendly, but the cost and timeframe of remediation are highly variable. The Federal Remediation Technologies Roundtable (FRTR) estimates that phytoremediation operation and maintenance can take anywhere from one to 30+ years depending on situation-specific factors like concentration and scale of contamination, climate, and vegetation characteristics. For high concentrations of contamination, phytoremediation can be used with other remediation technologies, absorbing the remaining contaminants in the final stages of a remediation project.

Phytoremediation

There are several sub-mechanisms of phytoremediation that have different implications for contaminant removal. For heavy metal contaminated soil, phytostabilization absorbs contaminants with the roots, phytoextraction translocates contaminants to plant parts above the soil surface. Contaminants that are translocated are then accumulated in the biomass of the plant through phytoaccumulation, valorized through photodegradation, or released into the atmosphere through phytovolatilization or evapotranspiration (Yan et al., 2020; FRTR). Phytostabilization, phytoextraction, and phytoaccumulation are the key processes involved in remediating heavy metal contaminated soil.

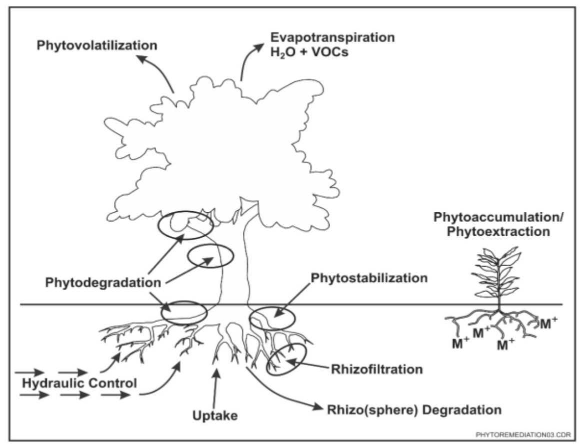


Figure 14: Phytoremediation
(Image credit: FRTR)

In general, plants that are ideal to utilize for phytoremediation purposes are fast-growing, have high biomass, extensive root system, and accumulate contaminants in the parts of the plant above ground that are easily harvestable (Nedjimi, 2021). Plants can be classified as avoidant, tolerant, or hyperaccumulators of contaminants (Yan et al., 2020). Tolerant plants are species whose growth is unaffected by contaminated soil. Hyperaccumulators are species that are able to uptake more than 1000 ppm contaminants which are 10x more than other species in the same environment (Vos et al, 2022; Yan et al., 2020).

Contaminants of Concern (COC)

Although there are various categories of contaminants, this review focuses on heavy metals (HMs). HMs are metallic chemical elements with high weight, atomic numbers, and densities that cannot be broken down by biological or physical processes (Yan et al., 2020). HMs are a category of soil contaminants that are a byproduct of agricultural activities like the application of pesticides and phosphate fertilizers; as well as industrial activities like mining, smelting, fossil fuel burning, and extraction. HM like copper (Cu), zinc (Zn), and nickel (Ni) are only toxic in high concentrations, while heavy metals like lead (Pb), Cadmium (Cd), and arsenic (As) are highly toxic at low concentrations (Yan et al., 2020).

5.2. Methods

A literature review of existing studies was conducted to explore the potential to use industrial hemp to remediate brownfields (Reeves et al., 2017; Angelova et Al., 2004), as well as the usability of contaminated biomass (Vos et al., 2022; Todde et al., 2022). Phytoremediation processes vary greatly depending on parameters like species-specific characteristics, the concentration of contamination, type of contaminant, the form of contaminant within the soil (Vos et al, 2022), as well as the moisture level and pH of the soil (Yan et al., 2020). Because of this, the conclusions below are offered as a generalized analysis to provide context around this idea but the implementation of industrial hemp for phytoremediation purposes should be evaluated on a case-by-case basis.

5.3. Industrial Hemp's Potential to Remediate HM Contaminated Soil

Industrial hemp has been demonstrated to be a contaminant tolerant species, but there is no evidence that it is a hyperaccumulator of heavy metals (Angelova et al., 2004; Reeves et al., 2017; Vos et al, 2022).

A field study completed by Angelova et. al (2004) tested the phytoremediation potential of industrial hemp, flax, and cotton using experimental plots of heavy metal contaminated soil near a Metal Works facility in Bulgaria. The results indicate hemp accumulated the highest amount of zinc, followed by lead, copper, and cadmium respectively (Angelova et Al., 2004). In this study, the flowers accumulated most of the heavy metals, followed by roots and stems.

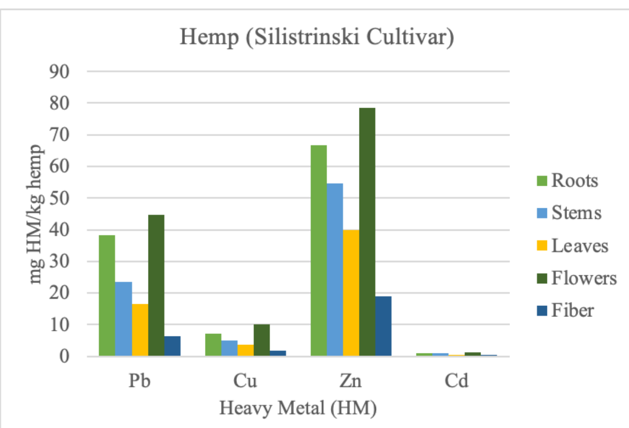


Figure 15: Accumulation of heavy metals by plant section

These results are in alignment with another study recently published by Vos et al (2022), although this study found higher HM concentration in the leaves of Cd and Zn; another insight suggests HM uptake can be greater in varieties with longer growing periods. This study also extended the analysis to estimate the annual removal potential of cadmium, zinc, and lead which is compiled in the table below. As mentioned previously in this paper and by other researchers (Vos et al, 2022, Angelova et al, 2014) phytoremediation is highly variable, so the results below are only one example for reference and should not be interpreted as the standard.

Heavy Metal	Cultivar	Min (kg HM/ha)	Max (kg HM/ha)
Cadmium	Carmagnola Selected and Santhica 70	0.0094	0.018
Zinc	Carmagnola Selected and Santhica 70	0.26	0.5
Lead	USO 31	0.12	0.22

Table 11: Accumulation of heavy metals by Cultivar

When looking at the results across species, this study found that flax had the highest HM accumulation potential followed by hemp, then cotton. With that being said, the flax plants did accumulate most of the HM within the root system which isn't easily harvested which is ultimately necessary to remove contaminants from the soil.

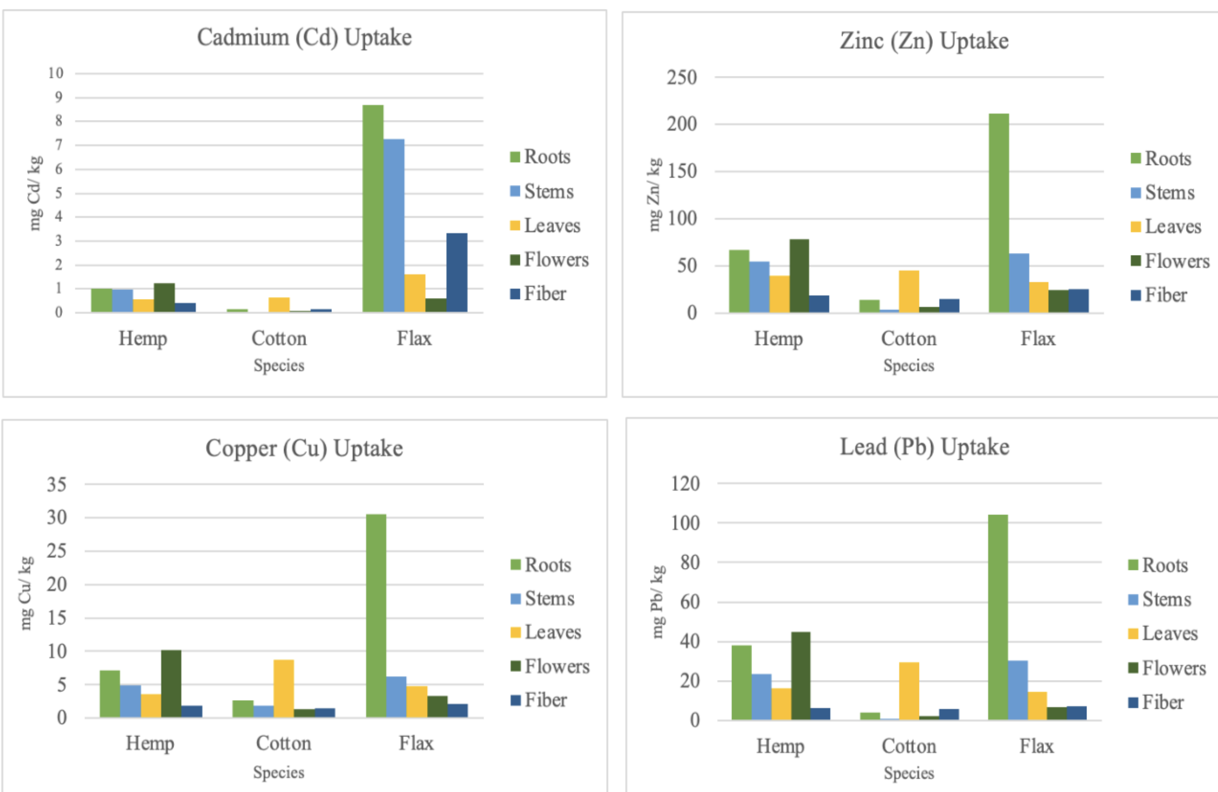


Figure 16: Accumulation of heavy metals by plant section for Hemp, Cotton and Flax

5.4. Post-remediation applications for HM Contaminated Biomass

Industrial hemp grown in contaminated soil must be properly managed post-remediation. The Solid Waste Disposal Act (U.S. Public law 89-272) and amendments should be referenced to guide applications of post-remediation biomass depending on the concentration levels of toxic elements (Song, 2017). There are several studies that have evaluated applications for industrial hemp biomass that was grown in HM-contaminated soil (Vos et al., 2022; Todde et al., 2022; Ying Jiang, 2015).

1. **Textiles**

   To determine whether biomass grown in HM contaminated soil could be used for textiles, Vos et al (2022) conducted a field experiment with 6 species of industrial hemp grown in experimental pots of sandy loam soil contaminated with lead, zinc, and cadmium that was collected 0.5 km away from a metal smelter in France. The study examined the 'early cultivars', USO 31 and Bialobrezskie, as well as the 'late cultivars' Carmagnola Select, Futura 75, and Dacia Secuieni. The fibers of the late cultivar, Carmagnola Selected, were evaluated for HM concentration from plants grown in a 'test' and 'control' plot to evaluate the toxicity of Cadmium (Cd), Lead (Pb), and Zinc (Zn). The plants grown in the test plot contained 1.7 mg of Cd ($\pm$0.5), 5.0 mg of Pb ($\pm$1.6), and 13 mg of Zinc ($\pm$2) per kg of fiber. By industry standards reviewed by Vos et al (2022) (OEKO-TEX, 2020) the levels of Cd and Pb are greatly below the toxicity limits (4o mg/kg for Cd, 90 mg/kg for Pb, no limits for Zn) and their research concludes that fibrous hemp grown in HM contaminated soil is likely suitable to be used for textiles (Vos et al (2022).

2. **Bioenergy production**

   Todde et al. (2022) examined the energy and environmental benefits of using the contaminated biomass for electricity and heat generation, specifically considering its use for biogas combustion and steam turbines. Although the author acknowledged the limited literature on this topic, they estimate the trace amounts of HM in the biomass has negligible impact on its usability for biofuel, but the atmospheric release of HMs should be more carefully considered to eliminate unintended contamination (Todde et al.). Ash is residual waste that is expected from biofuel production. The ash residual is expected to contain HM and requires adequate management. Pretreated ash can be used to produce high-density glass-ceramics (Todde et al., 2022). With that being said, if biofuel is an application of interest, the chemical composition of the given species of hemp should be analyzed for biofuel suitability. This is explained in depth by Gandolphy et al. (2016) who evaluated the fibrous Carmagnola species for biofuel applications and concluded it as a suitable species. There are 24 utility entities in Oregon who use biomass as their primary energy source (EIA, 2022).

3. **Industrial Applications using Hemp Hurd**

   Again, referencing results from the research of Vos et al (2022), the concentration of Cd was 0.62-1.07 mg/kg, Pb was 2.71-13.51 mg/kg, and Zn was 7.92-16.39 mg/kg. Santhica 70 variety had the highest concentration of Cd with 1.07 mg/kg, and USO had the highest concentration of Pb and Zn observing 13.51 mg/kg and 16.39 mg/kg respectively. Therefore, it may be possible to use raw materials for industrial uses post-remediation depending on maximum allowed concentrations of heavy metals.

Based on the literature reviewed, industrial hemp is expected to accumulate low concentrations of HM within the harvestable parts of the plant. There are some strategies to increase the phytoremediation potential like the use of rhizobacteria, genetic engineering, and increasing bioavailability of HM (Yan et al., 2020), uptake of HM in lower concentrations is a benefit in terms of post-remediation applications. On the other hand, considering the low levels of HM uptake of industrial hemp, brownfield restoration could take an extremely long time and may not be favorable for time-sensitive projects. In any case, this remediation strategy should be considered and evaluated in the context of a specific project.

6. Applications for the State of Oregon

6.1. Growing industrial hemp in Oregon

Preliminary soil survey conducted using an online tool from the Natural Resources Conservation Department indicated high acreage of cropland suitable for growing industrial hemp in Oregon with the highest suitability in Umatilla and Morrow Counties which are highly productive agricultural region growing potatoes, alfalfa and wheat. There are also multiple suitable areas with easy access to Portland highlighting the possibility of a processing industry to be based close to Portland.

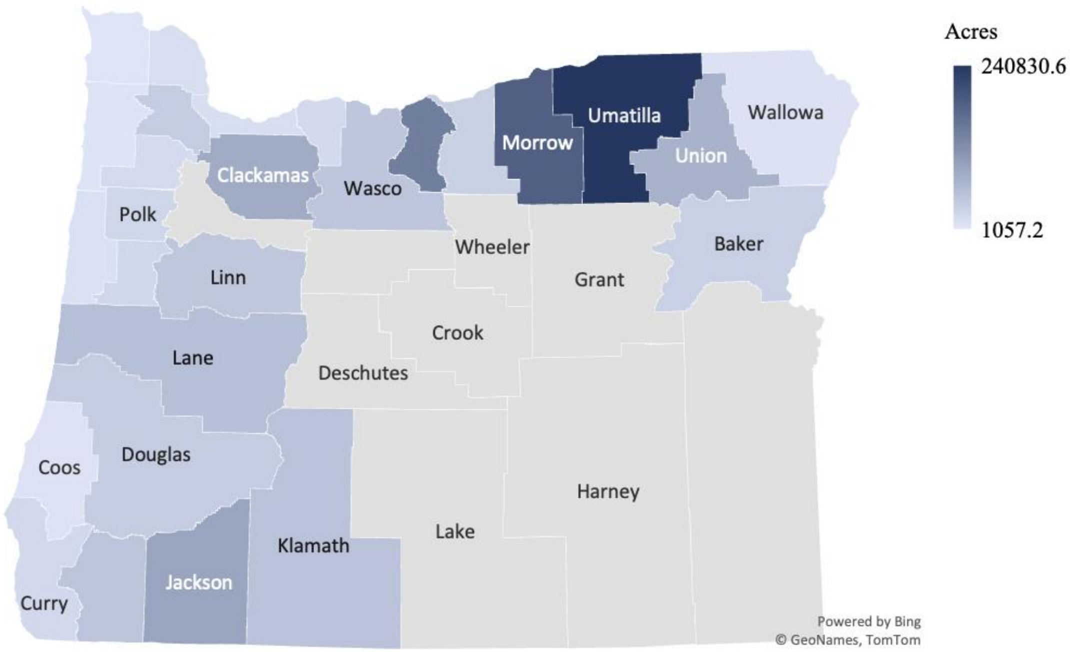


Figure 17: Acres of suitable and well-suited soil for growing Hemp by county.

Umatilla and Morrow Counties show promise for scalable growth of Oregon's industrial hemp industry. The results of our evaluation indicate Umatilla and Morrow have the most acreage of 'suitable' soil for growing fiber and oilseed/grain varieties of industrial hemp (Index___). The model used for the soil survey tool used to make this conclusion evaluated the soil suitability based on the primary conditions including slope, soil drainage, frost-free days, rocky ground cover; and secondary conditions of water storage available, organic matter, pH, electrical conductivity cation exchange, capacity, and hydraulic conductivity. If any of the primary conditions were present, the soil was considered 'unsuitable' since these variables are difficult to change (USDA).

Figure 18: Potential supply chain for hemp-based insulation

Umatilla and Morrow counties are split between the Columbia Plateau and Southeast Oregon agricultural regions. The Columbia Plateau is a highly productive agricultural region for growing crops like potatoes, onions, watermelons, and alfalfa (ODA, 2022). It is also Oregon's primary source of wheat production and has one of the country's largest dairies (ODA, 2020). The Southeast agricultural region is drier and livestock is the primary agricultural activity, but farmers also grow potatoes, onions, and beats (ODA, 2020). When grown as a rotational crop, it's best to grow alfalfa, potatoes, or legumes before hemp because of its nutrient requirements for growth (Alberta Agriculture and Forestry, 2020). Winter wheat is the best crop to grow after a hemp crop. Several field studies have indicated that farmers can cultivate a 10-20% higher yield of winter wheat when it's grown after an industrial hemp crop (Robson, 2002). These counties are well-suited in terms of existing agricultural activity and soil suitability, but they are also relatively close to the City of Portland (approximately 215 miles of useful distance traveled).

6.2. Financial mechanisms to support Hemp Fiber Production

Oregon's Natural and Working Lands proposal states, 'investments can be made through grants programs administered by OWEB and NRCS' and that 'DEQ should be encouraged to work with Tribes and stakeholders to solicit and fund projects that result in net carbon sequestration.' Given that hemp-based construction materials like hemp-lime insulation are demonstrated to be carbon negative, it would be advantageous to engage with the agencies that are involved in carbon sequestration projects for the state of Oregon.

The Natural and Working Lands Proposal also suggests a feasibility study should be conducted to identify potential funding mechanisms to support natural and working lands sequestration strategies in the state of Oregon and pointed to a study completed by The Trust for Public Land and The Nature Conservancy for the state of Wisconsin (Weinstein et al., 2020). Future research is recommended to identify how funding mechanisms that incentivize carbon sequestration could support hemp fiber production in Oregon.

New Market Tax Credits (NMTC): Tiger Fiber Inc, a hemp fiber company based in St. Louis secured $7 million in tax credit financing that they are using to expand their operational facility

(Nixon, 2022). Oregon is not currently accepting applications for this program, but it could be a financial lever that could be utilized if the program is active in the future.

Carbon offset programs: Oregon has 19 offset projects orchestrated by the American Carbon Registry, the Climate Action Reserve, and Verra. Offset projects are evaluated on the amount of GHG emissions permanently removed for each offset credit they receive (Burtraw et. Al, 2019). Climate Action Reserve supports projects that reduce GHGs outside of the established cap, have existing barriers for implementation, and have an analysis that supports the project's potential significance.

Federal Grants

EPA grants: Earth Merchant, a small business based out of Washington, makes hemp-based ‘OlogyBricks’. Last year, the company was awarded a $100,000 grant from the Environmental Protection Agency (EPA). They claim that the product “will improve energy efficiency and indoor air quality in single-family homes and other architectural applications” (Jaeger, 2021).

Department of Energy Grants: Texas A&M University received $3.74M from US Dept of Energy for researching 3d printing with hempcrete.

https://www.hempbuildmag.com/home/texas-a-m-3-d-hempcrete

7. Conclusion

In this report we explore the factors that impact the economic feasibility of processing hemp, present a detailed analysis of the carbon benefits of selected hemp material and conduct a literature review on the phytoremediation potential of hemp.

Hemp fiber must undergo a process to separate the usable fiber from the rest of the plant for use in industrial production. The separation and sorting of hemp fiber is done with specialized equipment called a decorticator, which removes the woody (hurd) and fine (bast) fibers from the hemp plant. The economic analysis conducted in this study focused on the purchase of decorticator and investigate the economic feasibility of obtaining one for Oregon's local hemp economy by constructing a scenario builder for decorticators of various costs and capabilities.

Overall, across all the simulations we have conducted we find that processing industrial hemp is likely to be profitable. We also find that the FiberTrack 660 has the fastest time to profitability/highest net revenue, but it's important to note that the economic feasibility is more sensitive to prices, cost, and other parameters than choice of decorticator. Therefore, each of the four decorticators is likely to be profitable and we recommend market studies to understand likely output prices and farmers surveys to inform decisions about likely yields and available amounts of inputs.

Next, we explored the potential carbon benefits of industrial hemp. We find that the cultivation of 1 mT of industrial hemp is expected to sequester 1.37 to 1.6 mT of CO_2. This would imply 3.151-3.68 mT of CO_2 is sequestered per hectare (ha) of industrial hemp cultivation assuming a conservative estimate of 2.3 mT of industrial hemp harvested per hectare. We extend the analysis to look at the carbon footprint of two hemp related products. We find that the production of one ton of hemp hurd is expected to sequester between 0.219 and 0.763 mT of CO_2 depending on the parameters of a given scenario.

This analysis was extended further to explore the carbon footprint of hemp-lime insulation, a buzz-worthy sustainable construction material made from hemp hurds, lime binder, and water. We estimate that 1 m^2 of wall insulated with hemp lime would result in approximately 10 kg of CO_2 sequestered or 6.24 kg of CO_2 emitted based on the various factors of the lifecycle previously discussed. In contrast, a 1 m^2 section of wall insulated with fiberglass is expected to result in 47.25 kg of CO_2e.

These results affirm that hemp-based construction materials would have a positive environmental impact in terms of CO_2 emissions, and could contribute to Oregon's emissions reduction goals. Oregon's Climate Action Plan includes plans to increase sequestration of natural and working lands and promote green building construction. Further, emerging hemp-lime products are capable of supporting structural loads which would eliminate traditional wood framing – potentially contributing to additional carbon benefits for a hemp-lime structure.

The final part of the study focused on the brownfield remediation potential of industrial hem. Based on the literature reviewed, industrial hemp accumulates low concentrations of heavy metals (such as Cadmium (Cd), Copper (Cu), Led (Pb), and Zinc (Sn)) within the harvestable parts of the plant. The phytoremediation potential can be increased with the use of rhizobacteria, genetic engineering, and increasing bioavailability of heavy metals. We also find that given the low-concentrations of uptake of heavy metals, hemp used to remediate brown fields can be used subsequently but in some cases may need proper management based on toxicity levels.

Since the hemp economy is resurging since legalization in 2018, there is also an opportunity to ensure it is developed in a way that provides equitable economic opportunities. Given that communities of color have traditionally been disenfranchised by cannabis, the new industrial hemp economy provides an opportunity to helps close racial equity gaps. The legalization also provides opportunities for indigenous tribes to reclaim the plant that has historically been used extensively across the country and the seeds of these efforts are already sprouting (Laduke 2021).

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Appendix 1: Input Parameters and Assumptions for the Economic Analysis

The cost of the decorticators include estimations of maintenance, labor, storage space, electricity, and rent for processing space based on each decorticator's capabilities. Estimates on these costs are derived using data available from the reference sources listed in Appendix 1. While this is not an extensive list of all cost and revenue variables included in the model, this presents the key variables that we felt would be most relevant for the reader.

Electricity prices	Commercial rate per kW hour (U.S. Energy Information Administration, n.d.).
Electricity usage	Decorticator specifications from manufacturer converted to kW/hr. and multiplied by days in operation and hours per day of operation. Assumed 10 hours of operation per day.
Labor costs, hourly wages	Hourly wages were based on information from the Oregon Employment Department for agricultural workers. Wages of $18.00/hr. multiplied by minimum labor required to operate each machine per manufacturer guidelines.
Rent costs for operational square footage	Annual rent per acre costs for Oregon agricultural land (United States Department of Agriculture, 2021) were divided by square feet per acre to arrive at per square foot cost. Assumed cropland used as site for decorticator operations. NOTE: If decorticator is located in Portland or another urban area the space rental rates would be higher.
Storage space	Storage costs assumed storage with bales of hemp straw stacked 2 high @ mass of .5 tons just under 36 square feet, (5x5 bale with additional clearance for working space) to calculate storage area. Bales can range from 500 pounds to 1 ton per bale, similar to straw (Banta, 2018). There are 43560 square feet in 1 acre divided by area per bale stacked 2 high is approximately 2419 bales per acre.
Composition	There is a wide range of fiber contained in industrial hemp plants, with fiber varieties/cultivars generating the most fiber per yield see (Găgeanu et al., 2020). Stalk refers to material that can be processed by the decorticator.
Output quantities	Output quantities are based on decortication processes and manufacturer claims. Decortication processes will yield hurd, bast and dust (Bouloc, 2013). We use proportions used in an economic analysis by Missouri state (Horner et al., 2019).

Table A1-1: References used for estimates of parameters and inputs

Assumptions Regarding the Decorticator Analysis

It is important to note that the results about economic feasibility presented in this report rest on some key assumptions and caveats, specifically

- The rental rate for the space for the decorticator is calculated based on farm land rental rates. If the decorticator is located in Portland or another urban area these rates will be higher.
- Transport to and from decortication facilities is costly
  - Framework can be expanded to include site locations
  - Also other costs (management/marketing/packaging) and product loss.
- No consideration of farmer opportunity costs (industrial vs CBD vs other crops).
  - Would need to do a farmer survey

- Ensuring standards regarding hemp fiber composition.
  - Farmer skill, growing and harvesting conditions, soil and cultivar/variety used impact composition
  - The composition influences decortication revenues as well as market demands.
- Qualitative differences in decorticator outputs are not considered
- Improvements in decortication machines can influence machinery price.

Finally, there are key factors about inputs factors and farmers' decisions which is outside the scope of this analysis that are important to consider in future analysis. Specially,

- A large factor in fiber volume and quality for industrial use is in the hands of farmers. This includes choice of cultivar, soil conditions, planting method, harvesting machinery, harvesting methods, storage conditions and opportunity costs. Farmer opportunity costs to include or switch to hemp fiber production from floral hemp, hemp grain, recreational marijuana, or other crop during the hemp growing season are not considered for this analysis. It may be beneficial to understand how the addition of a local decorticating facility impacts their opportunity costs and the decision to produce fiber.
- Testing and transport of the raw material to the decorticating site are not included in this analysis, and we assume these are covered by the farmer. An economic analysis regarding the production of hemp in Oregon may be necessary to understand how farmer decisions can impact the hemp fiber supply chain.
- The entire harvest is bought by a processor as an input for decortication.
- The decorticator is not financed.

Licensure for hemp processors, including all employees that are part of the decortication process, are not considered. Not to be confused with licensing for the Canadian Greenfield Hemp Train.

Appendix 2: Carbon Footprint Equations and Tables

Table A2-1A: Harvestable Yield of Fibrous Hemp by Location

Location	Dry hemp (mT/ha)	Dry hemp (Kg/ha)	Source
Oregon	2.3	2,300	USDA, 2021
U.S.	3.0	3,000	Congressional Research Service, 2019
France	6.7	6,700	Van-der-Werf, 2004
UK	7.5	7,500	DERFA, 2005
Canada	8.2	8,165	Alberta Agricultural Department, 2014

Table A2-1B: Harvestable Yield by Varietal

Varietal	Dry hemp (mT/ha)	Source
Białobrzeskie	6.8-10.8	Luhr, 2018; Katarzyna, 2022
Futura 75	7.8-11.5	Luhr, 2018, Vos, 2022
Santhica 70	12.32	Vandepitte et al., 2020
USO 31	7	Vandepitte et al., 2020

Table A2-1C: Emissions factors

Category	Raw material	CO2 Emissions Factor (mT of CO2)	Source
Mineral	Calcite (limestones)	0.43971	U.S. EPA, 2018
Mineral	Dolomite	0.47732	U.S. EPA, 2018
Fuel	Diesel	0.01019	EIA, 2021
Energy	Natural gas	0.44967	U.S. EPA, 2020
Energy	Hydropower	0.000024	IHA
Element	Nitrogen	0.00498	Baral et al., 2020
Element	Phosphorus	0.00103	Baral et al., 2020
Element	Potassium	0.00055	Baral et al., 2020

Emissions Sequestered by Industrial hemp

Photosynthesis: $\boldsymbol{CO_2 + H_2O \rightarrow C_6H_{12}O_6 + O_2}$

Equation 1:

$$\boldsymbol{HempES_i} = \frac{EF_C}{\lambda_{lig} \cdot M_{lig} + \lambda_{cel} \cdot M_{cel} + \lambda_{hem} \cdot M_{hem}} \cdot -1$$

Where:
$\boldsymbol{HempES_i}$ is the CO_2 sequestered through photosynthesis by hemp variety i
λ_{lig} is the percentage of carbon of lignin
λ_{cel} is the percentage of carbon of cellulose
λ_{hem} is the percentage of carbon of hemicellulose
M_{lig} is the mass of lignin
M_{cel} is the mass of cellulose
M_{hem} is the mass of hemicellulose

Emissions from Soil Fertility Management

Equation 2:

$$\boldsymbol{E_{SoilTon}} = \frac{\boldsymbol{E_{AgHa}}}{\boldsymbol{M_{HempHa}}}$$

Where:
$\boldsymbol{E_{SoilTon}}$ is the estimated $\boldsymbol{CO_2}$ emitted per ton of fibrous hemp grown
$\boldsymbol{E_{SoilHa}}$ is the estimated $\boldsymbol{CO_2}$ emitted per Ha
$\boldsymbol{M_{HempHa}}$ is the tons of dry hemp produced per ha assuming 2.3 ton dry hemp per hectare (USDA, 2021).

Table A2-2: Emissions per soil fertility management

Soil Fertility Management	E_{SoilHa}	$E_{SoilTon}$
Good agricultural practice	2.33	1.01304348
Pig slurry	1.77	0.76956522
Reduced tillage	2.20	0.95652174
Less leaching	2.09	0.90869565

(Hayo M.G. Van der Werf, 2004)

Emissions from Farm Machinery

Equation 3:

$$\boldsymbol{E_{FarmMach}} = \frac{\boldsymbol{Gal_{diesel}}}{\boldsymbol{M_{HempHa}}} \cdot \boldsymbol{EF_{fuel}}$$

Where:

$\boldsymbol{E_{FarmMach}}$ is the estimate of $\boldsymbol{CO_2}$ emitted by the farm machinery per ton of industrial hemp
$\boldsymbol{Gal_{diesel}}$ is the gallons of diesel burned per hectare ($\boldsymbol{M_{HempHa}}$) assuming 2.3 ton dry hemp per hectare (USDA, 2021)
$\boldsymbol{EF_{fuel}}$ is the emission factor from fuel assuming 0.01019 tons CO_2 is emitted/gallon of diesel

Table A2-3: Emissions per farm machinery

Process	Farm Machine	Fuel (diesel gal/Ha)	E_{AgHa}	E_{AgTon}
Plowing	Massey Ferguson Tractor	3.52	0.03580634	0.01536753
Harrowing	Massey Ferguson Tractor	3.52	0.03580634	0.01536753
Seed drilling	150 hp John Deere	3.51	0.03580634	0.01536753
Rolling	151 hp John Deere	1.32	.013461030	0.00577727
Harvesting	Tractor driven reaper- 4 blade multi reaper	1.32	.013461030	0.00577727
Retting	Tractor driven reaper- 4 blade multi reaper	0.26	.002692206	0.00115545
Baling	Large bailer	3.96	0.04038309	0.0173318
Total	All of the above	17.41	0.17739709	0.07613609

Emissions from useful distance traveled

Equation 4:

$$\boldsymbol{VehE_i} = \sum_{\boldsymbol{i=0}} \frac{\boldsymbol{d_{total}}}{\boldsymbol{MPG_{veh}} \cdot \boldsymbol{OC_{veh}}} \cdot \boldsymbol{EF_{fuel}}$$

Where:

E_{veh} is the CO_2 emitted by during useful distance traveled
d_{total} is the total useful distance traveled ($d_A + d_B$)

$$d_A = Industrial\ hemp\ \rightarrow\ Warehouse$$
$$d_B = Other\ raw\ materials\ (lime\ binder, etc.) \rightarrow\ Warehouse$$

MPG_{veh} are the miles per gallon of diesel for a fully loaded vehicle
OC_{veh} is the transportation capacity of the vehicle in metric tons
EF_{fuel} is the emissions factor of fuel

Table A2-4: Emissions from the transportation of raw materials

Class 8 Vehicle Type	Fuel Units	MPG empty	MPG_{veh}	OC_{veh}	EF_{fuel}
Conventional	gal. of diesel	8.6	4.23	15.875	0.01019
Fuel Cell Hybrid Electric	gal. of diesel eq.	10.1	5.29	15.875	0.01019
Fully Electric	kWh of electricity	22.9	11	15.875	0.000024

**assuming highway driving on a paved, undamaged road* (Baral et al., 2020)

Table A2-5: Emissions from useful distance traveled

d_{total}	$VehE_{conventional}$	$VehE_{hybrid}$	$VehE_{electric}$
50	0.0075873	0.0060670	0.0000069
100	0.0151747	0.0121340	0.0000137
150	0.0227620	0.0182010	0.0000206
200	0.0303494	0.0242680	0.0000275
300	0.0455241	0.0364021	0.0000412
400	0.0606988	0.0485361	0.0000550

Emissions from decorticator used to process hemp fiber

Equation 5:

$$Hr_{tHurd} = \frac{1}{Mhemp_i \cdot \lambda_{hurd}}$$

$$\boldsymbol{DecE_i = Hr_{tHurd} \cdot \left(kWh_{tHemp} \cdot Mhemp_i\right) \cdot EF_{Pow}}$$

Where:
$\boldsymbol{DecE_i}$ is the estimated $\boldsymbol{CO_2}$ from producing 1 mT of hemp hurd with decorticator i
$Mhemp_i$ is the average metric tons of hemp processed per hour by decorticator i
λ_{hurd} is the proportion of hurd output
Hr_{tHurd} is the number of hours it takes to produce 1 mT of hurd
EF_{Pow} is the CO_2 emissions factor per kWh of power

Table A2-6: Emissions from decorticator processing

Decorticator Model	Hr_{tHurd}	$\boldsymbol{DecE_i}$
HempTrain HT-UF	1.4286	0.003257143
FiberTrack 660	0.9524	0.004182857
Hurd master micro	25.9740	0.000934971

Emissions of producing the lime binder

Equation 6:

Calcination of pure limestone: $CaCo_3 + heat \rightarrow CaO + CO_2$

$$E_{lime\ binder} = M_{ql} \cdot EF_{ql} + M_{dl} \cdot EF_{dl}$$

Where:
EF_{ql} is the emissions factor of quick lime
EF_{dt} is the emissions factor of dolomite
M_{ql} is the mass of lime
M_{dl} is the mass of dolomite lime

Emission from Hemp-lime (based on mixing ratio)

Equation 7:
$M_{hemplime} = (\lambda_{hurd} \cdot E_{hurd}) + (\lambda_{lime} \cdot E_{lime\ binder})$
Where:
λ_{hurd} is the percentage of hurd
0.5 for 1:1 ratio
0.34 for 1:2 ratio
λ_{kWh} is the percentage of lime
0.5 for 1:1 ratio
0.64 for 1:2 ratio

Emissions from Hemp-lime installation

Equation 8:
$E_{instal} = kWh_{instal} \cdot EF_{Pow}$
Where:
E_{instal} is the estimated emissions from installation
kWh_{instal} is the electricity expected per ton of hemp-lime installed
EF_{Pow} is the CO_2 emissions factor per kWh of power

Table A2-7: Emissions from installation of hemp-lime insulation

Method	Electricity (kWh)	$\boldsymbol{E_{instal}}$
Spray Infill	1.5	0.000036
Form Infill	1.2	0.000029

(IP and Miller, 2012)

Equation 9:
$\boldsymbol{E} \quad = \boldsymbol{E_{Hemp-lime}} + E_{Hemp-limePlaster}$
Where:
$E_{Hemp-lime}$ is the estimated emissions producing and installing hemp-lime insulation used for 1 m^2 wall

Table A2-8: Emissions from installation of hemp-lime insulation

	Product type	R-value	Min Emissions (kg of CO2)	Max Emissions (kg of CO2)
Sheathing	Hemp-lime plaster	5	-2.46	1.57
Sheathing	Hemp-lime plaster	10	-4.92	3.13
Cavity	Hemp-lime	14	-6.89	4.38
Cavity	Hemp-lime	15	-7.34	4.67
Cavity	Hemp-lime	16	-7.88	5.01

Equation 10:

$$\boldsymbol{GWP} \quad = \boldsymbol{E_{RigidInsulation}} + E_{UnbondedLoosefill} + E_{Plasterboard}$$

Where:

$E_{Hemp-lime}$ is the estimated emissions producing and installing hemp-lime insulation used for 1 m^2 wall

$E_{Hemp-limePlaster}$ is the estimated emissions producing the plaster used for 1 m^2 wall

Table A2-9: Emissions from hemp-lime wall

	Product Type	Product	R-value	GWP (kg CO2e)
Sheathing	Rigid Insulation	FOAMULAR® 150 XPS Insulation	5	39.57
Sheathing	Rigid Insulation	FOAMULAR® 150 XPS Insulation	10	79.09
Cavity	Unbonded Loosefill	PROPINK® L77 PINK® Fiberglas™	14	3.13
Cavity	Unbonded Loosefill	PROPINK® L77 PINK® Fiberglas™	15	3.64
Cavity	Unbonded Loosefill	PROPINK® L77 PINK® Fiberglas™	16	5.51
NA	Plasterboard	Gypsum wallboard	-	4.04

Table A2-10: Parameter Tables

		Fiber	Oilseed/grain	Flower
Planting	**Time**	Mid-late May	May – June	Late May to Mid-June
	Method	Grain drill	Grain drill	Transplanter
	Density	1.3-1.5 (mil seed/acre)	.435-.653 (mil seed/acre)	1000-2500 plants/acre
Harvest	**Method**	Sickle-bar	Combine	Cut by hand
	Post-harvest handling	Retting, baled	Cleaned and dried	Hang dry, then strip flowers
Post-harvest	**Storage**	Cover bales	Grain bins 8-10% moisture	Large totes with low moisture
	Processing	Decorticators	Food processors	Extractors
	Height (ft)	10-16	4-8	4-10
Crop appearance	**Appearance**	Tall slender	Single grain head on the end of stalk	Bushy plants with multiple flowers
	Material	Fiber, Hurd	Fixed oil, Seeds	CBD, other oils

(Alberta Agriculture and Forestry, 2020)

Varietal	**Dry hemp (mT/ha)**	**Source**
Białobrzeskie	6.8-10.8	Luhr, 2018; Katarzyna, 2022
Futura 75	7.8-11.5	Luhr, 2018, Vos, 2022
Santhica 70	12.32	Vandepitte et al., 2020
USO 31	7	Vandepitte et al., 2020

Location	**Dry hemp (mT/ha)**	**Dry hemp (Kg/ha)**	**Source**
Oregon	2.3	2,300	USDA, 2021
U.S.	3.0	3,000	Congressional Research Service, 2019
France	6.7	6,700	Van-der-Werf, 2004
UK	7.5	7,500	DERFA, 2005
Canada	8.2	8,165	Alberta Agricultural Department, 2014

Table A2-11: CO2 emissions factors

		CO2 Emissions	**Source**
Mineral	Calcite (limestones)	0.43971	U.S. EPA, 2018
Mineral	Dolomite	0.47732	U.S. EPA, 2018
Fuel	Diesel	0.01019	EIA, 2021
Energy	Natural gas	0.44967	U.S. EPA, 2020
Energy	Hydropower	0.000024	IHA
	Nitrogen	0.00498	Baral et al., 2020
	Phosphorus	0.00103	Baral et al., 2020
	Potassium	0.00055	Baral et al., 2020

Table A2-12: Prices of offsets

Project	**Price per mT of**	**Source**
California and Quebec Cap-and-trade program	$16.46	California Air Resources Board (2022)
East Texas Farm Project	$5.08	(Ribera and McCarl)
Social cost of carbon	$42-	(EPA

Table A2-13: Expected gross returns for crop production offset project

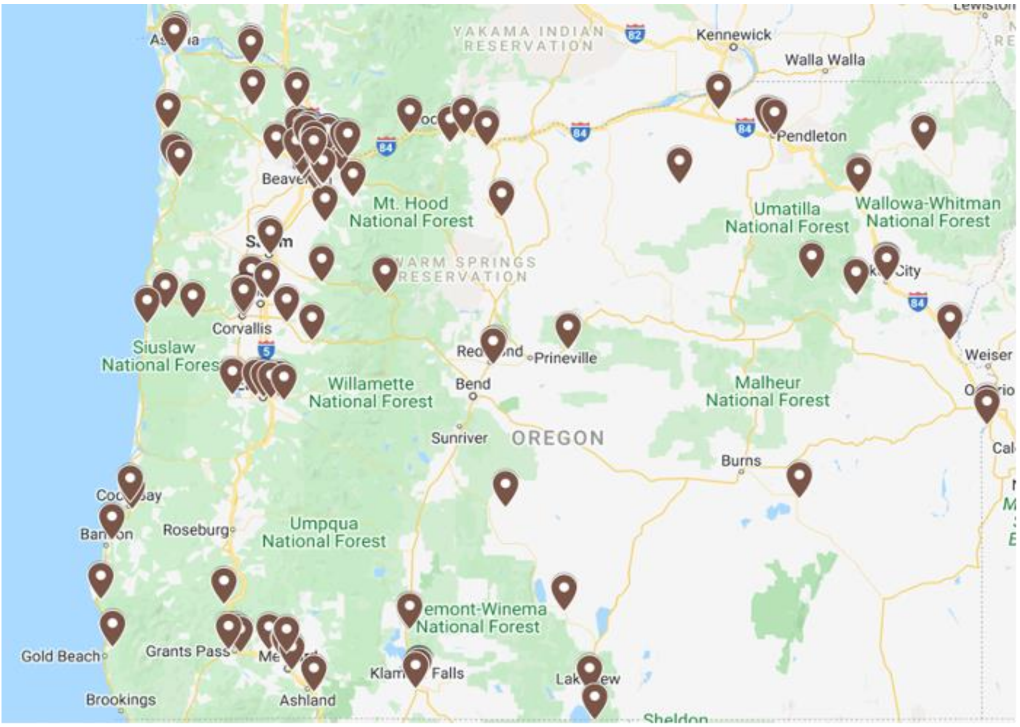
Market price ($/t)	$6.00
Fees (registration, trading, etc.)	$0.48
Actual price	$5.52

(Ribera and McCarl)

Rate of sequestration	1.57

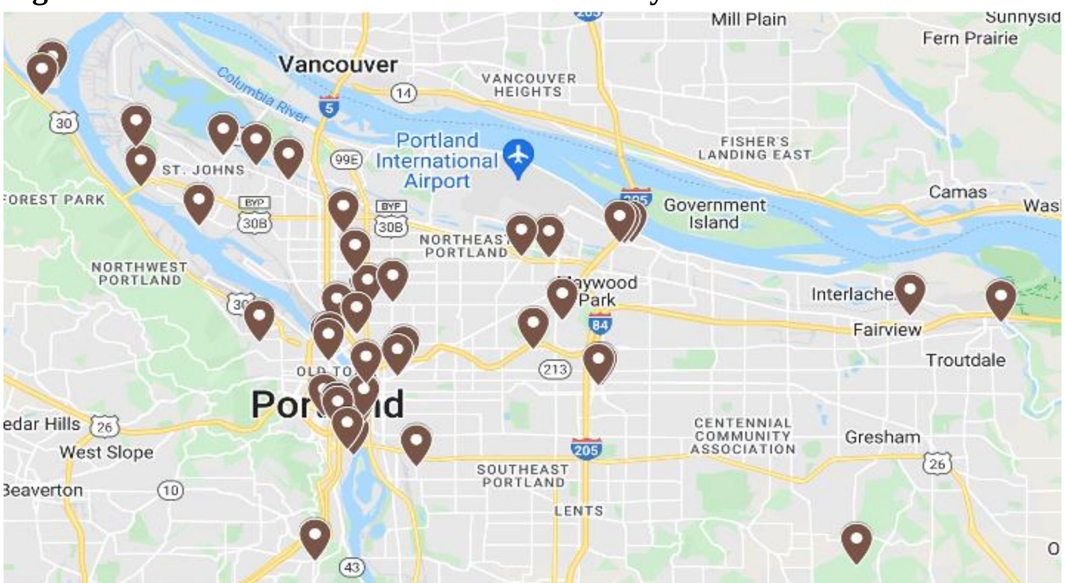
Appendix 3: Brownfields Analysis

Figure A3- 1: Brownfields in Oregon (Source: ECSI Database, OR DEQ)



Source: ECSI Database, OR DEQ

Figure A2-2: Brownfields in Multnomah County



Source: ECSI Database, OR DEQ