

Reaping What You Sew:  
Evaluating the Sustainability of Natural Fiber Crop Production in the Southeastern United States  
An Independent Research Capstone Project for the Degree of Master of Liberal Arts  
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December 8, 2018

### Abstract

The increased demand for sustainable natural fibers is a direct result of the growing awareness of the social, economic, and environmental impacts caused by the overproduction and overconsumption of synthetic fibers. As consumers and brands along the fiber supply chain seek a natural alternative to synthetic, the opportunity for American farmers to cultivate the natural fiber crops grows. Some of the most frequently produced and utilized natural fiber crops, such as cotton, flax, and hemp, have been cultivated in the United States since the pre-Revolutionary era. However, the global fiber market's shift to using essentially only synthetic fibers and conventionally-produced cotton created a centuries-long decline in the production of these alternative natural fiber crops on American farms.

Because the cultivation of natural fiber crops other than cotton, like flax and hemp, is essentially non-existent in today's American agricultural sector, resources to aid farmers in natural fiber crop planning and production are limited. Further, the demand for natural fibers is an outgrowth of the global sustainability movement, in which consumers desire products that are responsibly-produced and have reduced negative impacts on people and the planet. Therefore, the resources farmers rely on to evaluate natural fiber crop production opportunities must be adapted to evaluate the multidimensional effects of sustainability of crop cultivation. Specific tools and resources that are able to holistically consider the social, economic, and environmental impacts of natural fiber crop production are better suited to assist farmers in selecting crops and cultivation methods to meet their goals and the demands of the market.

A chief objective of this research is to fill the gap in farmer resources for fiber crop cultivation by evaluating the sustainability of producing natural fiber crops. This evaluation is accomplished through the construction of an empirical framework using the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE), a Multicriteria Decision Analysis (MCDA) methodology. For the purposes of this research, *alternative natural fiber crops* include flax, hemp, and organically-produced cotton. The PROMETHEE evaluation in this study consisted of two scenarios that analyzed the production of natural fiber crops against selected social, economic, and environmental criteria to index them based on their overall sustainability.

First, PROMETHEE was used to analyze the production of four popular natural fiber crops: conventionally-produced cotton, flax, hemp, and organically-produced cotton. Secondly, PROMETHEE was used to evaluate a set of three alternative natural fiber crops—flax, hemp, and

organically-produced cotton. In this paper, conventionally- and organically-produced cotton will be referred to as conventional cotton and organic cotton respectively.

These natural fiber crops were selected for evaluation because they are adaptable to cultivation in the southeastern United States, a region with a long history of, and high potential for, natural fiber crop production. The results of the first PROMETHEE evaluation found conventional cotton to be the most sustainable, though marginally. The second evaluation of alternative natural fiber crops determined hemp was the most sustainable crop, followed by flax as the second-most sustainable crop, and organic cotton as the least sustainable crop. An examination of the barriers to viable, commercial-scale hemp production in the United States, and improvements to the PROMETHEE evaluation is included.

While PROMETHEE is increasingly applied to analyze crop cultivation and aid in on-farm decision-making, this research's PROMETHEE evaluation of the sustainability of natural fiber crop production is a novel application of the methodology for this purpose. This original analysis results in a practical index of natural fiber cultivation within the southeastern United States based on social, economic, and environmental attributes. More importantly, this research provides a useful, analytical process that can be applied to future evaluations of fiber crop cultivation, as well as a modifiable framework to help farmers make informed decisions on crop planning and production that account for the multiple dimensions of sustainability.

*Keywords:* cotton, flax, hemp, natural fiber, multicriteria decision analysis (MCDA), PROMETHEE, sustainability, southeast, United States

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## Reaping What You Sew:

### Evaluating the Sustainability of Natural Fiber Crop Production in the Southeastern United States

#### **Introduction**

While the fibers from a wide variety of crops have been utilized to create garments and other textiles for hundreds of years in the United States, the cultivation of these crops across the country has experienced a steady decline over the last century. This reduction in natural fiber crop production is a result of the current reliance on cotton and synthetic fibers. Despite the importance of flax and hemp production from the pre-Revolutionary era through the late eighteenth century, the demand for cotton, which was supported by the invention of the cotton gin in 1793, secured cotton's place as the dominant fiber crop produced in the United States thereafter (Fisher, 2006). The production and use of synthetic fibers, derived from nonrenewable, petrochemical feedstocks, outpaced the cultivation and processing of natural fiber for textiles beginning in the 1950s (Jefferson Institute, n.d.). This trend continues today as these synthetic and cotton fibers account for the majority share of the global fiber market.

As a result of these trends and technological developments, the cultivation of natural fiber crops by American farmers, save for cotton, is essentially non-existent currently. Yet, the demand for textiles and products derived from sustainably- and domestically-produced natural fibers is growing. Driving this trend is the increasing awareness about the advantages of natural fibers over synthetics. Some of these benefits include a reduction in the use of chemicals and natural resource consumption, as well as increased revenues for farmers (Grand View Research, 2017). In order to meet the market demand, the scale of cultivation of natural fiber crops will need to be expanded on American farms. However, in order to grow the supply of natural fibers, farmers require production resources and frameworks that can evaluate the social, economic, and environmental impacts of natural fiber crop cultivation, illuminating the both the costs and benefits of the production.

At present, no existing tools, models, frameworks, or resources exist to allow farmers to analyze fiber crop production in agricultural systems within the United States.

Accordingly, the two primary objectives of this paper were to:

1. Construct an empirical framework to evaluate two natural fiber cultivation scenarios:



- a. The first scenario analyzed cultivation of conventionally-produced cotton, flax, hemp, and organically-produced cotton, and;
  - b. The second scenario evaluated *alternative natural fiber crops* flax, hemp, and organically-produced cotton.
2. Systematically index the crops based on their overall sustainability performance against selected social, economic, and environmental criteria.

The crop data used for evaluation were derived from resources that documented actual production of the selected natural fiber crops in the southeastern United States. This region has a history of natural fiber crop production and, therefore, was selected as the spatial frame of the analysis. Despite the limits of the geographic scope of this evaluation, the resulting framework and creation of a *Natural Fiber Crop Sustainability Index* provide a foundation for manipulatable evaluation method and framework to model fiber crop cultivation.

### **History of Natural Fiber Cultivation**

Humans have produced and processed the fibers from plants into textiles for millennia. Evidence of linen fiber textiles, spun from flax cultivated by the Swiss Cave Dwellers, date back to 8000 BC, while cotton fiber was being used Mexico in 5000 BC and India and Pakistan in 3000 BC (Fisher, 2006). Natural fibers are those derived from the cellulose found in plant seeds, leaves, bast cores, fruit, and stalks of crops like abaca, bamboo, coir, cotton, flax, hemp, jute, kenaf, ramie, and sisal (Food and Agricultural Organization of the United Nations, 2009). Around the world, dozens of fiber plants have adapted to a multitude of climates, and while their species differ, fiber crops share inherent environmentally-sustainable characteristics. As agricultural products, natural fiber crops are annually renewable, fixing carbon dioxide through the photosynthetic process into the plant's cellulosic matter (Baines, n.d.; Islam & Mohammad, 2016). In the case of many fiber plants, byproducts and waste can be utilized as biomass fuel, construction and industrial material applications, ingredients in food, cosmetic, and pharmaceutical products, or returned as compost matter to enhance soil fertility and structure. Finally, when natural fibers are used in their raw state, processed without added chemicals, they are readily biodegradable and recyclable at the end of their useful life (Baines, n.d.; Ramawat & Ahuja, 2016).

Thousands of years after the earliest recorded cultivation, natural fibers are still grown and processed around the globe for a variety of purposes; however, their total share of the global

fiber market has diminished since the mid-twentieth century due to the invention of synthetic fibers. Today, just 40% of the world fiber market, which totals over 100 million tons, is supplied by natural fibers. Cotton composes 85% of this natural fiber total, with the remainder made up of fibers derived from crops like hemp, flax, and other cellulosic plants (Food and Agricultural Organization of the United Nations, 2009; Kelley, 2017). The remaining 60% of the global fiber market consists of synthetic fibers, of which petroleum-derived polyester accounts for more than half of the total at 55% of all synthetic fibers produced (Ellen MacArthur Foundation, 2017).

### **The Growth of Synthetic Fiber Production**

Advances in polymer science and materials technology spurred the increased production and use of synthetic fibers, specifically in the global textile industry. Since 1980, the total market share of synthetic fibers has grown at a nearly 5% compound annual growth rate (Nonwovens Industry, 2017; Samanta, Basak & Chattopadhyay, 2016). The production of synthetic fibers for textile applications has doubled since 1990 to nearly 15.6 pounds of the total 26 pounds of fiber produced per capita (Claudio, 2007; Kelley, 2017). Subsequently, the decline in the use of natural fibers in favor of synthetic fibers has created considerable negative social, economic, and ecological impacts on society and the environment, which are described in the subsequent sections.

**Environmental Costs of Synthetic Fibers.** The production of synthetic fibers, and the textiles derived from them, requires the energy intensive extraction of non-renewable petroleum resources, which creates toxic releases of hazardous pollution and waste into the environment. The manufacturing of fibers and production of textiles emits particulate matter, volatile organic compounds, harmful gases, salts and surfactants, heavy metals in dyes, chemical solvents for coatings and treatments, and other pollutants into the air- and waterways. According to Kelley (2017) the textile industry, where a vast majority of fibers and textiles are produced, ranked third among all industries in wastewater discharge total and second in water pollution, as measured by chemical oxygen demand (Kelley, 2017). Further these toxic releases have deleterious effects on ecosystems and human health, including linkages to bladder, lung, colorectal, and breast cancers (Allwood et al., 2006; Claudio, 2007; Kelley, 2017).

As stated previously, the textile industry is a significant consumer of these synthetic fibers. At present, the current production of textiles requires 25% of all chemicals manufactured

worldwide, of which the majority are used for synthetic fiber and products made from them (Kelley, 2017). Moreover, as stated by Kelley (2017) the textile industry is responsible for 5% to 10% of total global greenhouse gas (GHG) emissions, totaling 1.2 billion metric tons of greenhouse gases. These emissions equate to more than all of the GHG emissions from all international flights and maritime shipping combined (Ellen MacArthur Foundation, 2017). According to a study by Cherrett, Barrett, Clemett, Chadwick, & Chadwick (2013) the carbon dioxide emissions from the production of one tonne of polyester fiber, measured by “the amount of land area required to provide all of the necessary resources and absorb associated carbon dioxide waste to produce a given unit of textile” accounts for 9.52 kilograms of carbon dioxide emissions, compared to 5.90 kilograms for conventional cotton production, and 2.35 kilograms for organic cotton fiber. Finally, according to Kelley (2017) and Claudio (2007), 10.5 million tons of fiber per year, or 70 pounds per capita, are disposed of in landfills annually where they are not expected to degrade for thousands of years.

**Socioeconomic Costs of Synthetic Fibers.** Fueled by the overproduction of synthetic fibers the textile industry is currently valued at more than \$1 trillion dollars (Allwood et al., 2006; Kozlowski, Bardecki & Searcy, 2012). However, this economic value is not equally distributed to all members of fiber supply chain. At present, synthetic fiber and textile production is concentrated in factories in developing nations that may not ensure living wages or safe working conditions for their employees who are exposed to toxic releases at much higher rates than the general population (Allwood et al., 2006; Claudio, 2007; Kozlowski, Bardecki & Searcy, 2012). This off-shoring of the textile industry, as a result of globalization and automation, negatively impacted the processing and manufacturing that once drove local and regional economies in the United States. For example, in the American southeast, textile production was a major, thriving industry through the mid- to-late twentieth century and anchored the economies of rural communities (Hamlin, n.d.). As stated by Hamlin (n.d.), prior to the elimination of domestic textile quotas in the North American Free Trade Agreement, the industry was the largest employer of women and people of color, who spun natural fibers produced by farmers in the region into fabric and textiles.

Farmers, specifically, are a link in the fiber supply chain negatively impacted by the growing dominance of synthetic fibers in the global fiber market and textile industry. The reduction in the use of natural fibers has diminished the livelihoods of farmers that produce

them. Today, opportunities in natural fiber production for farmers are limited to the production of cotton, the dominant fiber crop grown and processed globally, in large-scale, conventional, monocrop systems. Cotton producers are forced to expand and intensify their production of cotton in order to increase yields in the hopes of compensating for the depression of market prices for natural fibers by synthetics (Food and Agricultural Organization of the United Nations, 2009). Despite the reality of the current fiber market, the demand for natural fibers, and products made from them, is growing, presenting a new opportunity for farmers to cultivate a diversity of natural fiber crops in farm systems.

### **Growing Demand for Natural Fibers**

Currently, the market for organic and natural fibers is experiencing a nearly 4% compound annual growth rate (Grand View Research, 2017). This market sector is estimated to reach \$37.3 billion by 2024 (Nonwovens Industry, 2017). Driving this demand is a rise in consumer consciousness, as evidenced in a survey of 500 Americans, wherein 66% percent indicated they would pay more for natural fibers and only 33% percent found synthetic fibers safe (Friedman, 2018). Analogous to the growth of the food and farm movement over the last few decades, in which consumer awareness of the effects of industrially-produced food has spurred an increased interest in and support for food produced in local and regional food systems, consumer consciousness about the impacts of synthetic fibers is influencing the increased demand for domestically produced, sustainable natural fibers.

Accordingly, brands are capitalizing on this consumer consciousness, creating more sustainable products that incorporate natural fibers. Companies like Giorgio Armani, Stella McCartney, Eileen Fisher, Levi Strauss, LL Bean, Patagonia, Nike, and The North Face have committed to designing textiles made from fibers like organic cotton, hemp, and flax to reduce the negative impacts that result from use of synthetic fibers. Notably, some brands are bypassing the traditional supply chain to engage farmers directly in producing high quality natural fibers in sustainable agricultural systems by purchasing entire harvests of crops before they are even sown.

One such company, Patagonia, has exclusively used United States-grown organic cotton in its apparel since 1996, and is now investing in the re-establishment of other domestically-produced natural fibers like hemp (Chouinard & Brown, 1997). In 2016, Patagonia partnered with California-based natural fiber production organization, Fibershed, and The Growing

Warriors Project, a farm service and advocacy group out of Kentucky, to support the production research plots of industrial hemp in Kentucky (Malloy & Dumain, 2016). These efforts bolster a regenerative and climate-beneficial textile system wherein farmers, and other members of the fiber and textile supply chain, work collaboratively to cultivate truly environmentally, socially, and economically beneficial natural fibers. Fibershed engages and supports farmers in producing a diversity of natural fibers from alpacas, angora rabbits, goats, llamas, sheep, cotton, flax, and hemp in regional agricultural systems across the United States (Fibershed, n.d.; Harrison, 2018).

### **Current State of Natural Fiber Crop Cultivation in the United States**

Despite the growing movement towards natural fibers, fiber crop cultivation in the United States is, and historically has been, heavily concentrated in cotton. The vast majority of cotton around the world is produced in monocrop, industrial systems. According to Kelley (2017), cotton is grown on 2.3% of global arable land, but requires 14% of all agricultural insecticides and 2.6% of global water use. Furthermore, production of cotton is responsible for 1% of all global greenhouse gas emissions (Kelley, 2017).

In the United States, cotton is cultivated in the southern and western regions, and has expanded tremendously since first cultivation records were kept in 1621 (Smith & Cothren, 1999; United States Congress, Office of Technology Assessment, 1987). Cotton production has a long, complex history in the southern region, as production intensified to meet the demand for the fiber after the invention of the cotton gin in 1793 (Smith & Cothren, 1999). The subsequent intensification of cotton cultivation led to a labor force of tens of thousands of slaves owned by cotton plantation owners. This labor structure instigated hundreds of years of racial conflict throughout the United States (Smith & Cothren, 1999). Today, the United States is the world's third largest cotton producer, planting 14 million acres (with an expected harvest of 19.7 million bales) in 2018, and is the top global cotton exporter (Meyer, 2018). Even though cotton will remain an important agricultural commodity in the United States, the demand for sustainably-produced alternative natural fibers, like flax, hemp, and organic cotton, provides an opening for American farmers to gain a foothold in the burgeoning natural fiber market.

Consequently, if American farmers are to capitalize on the opportunity to produce with alternative fiber crops that provide a strong supply of sustainable natural fiber, they require data, models, and resources that can analyze the social, economic, and environmental impacts of the crop cultivation. To the best of the author's knowledge, no models, nor methodologies, exist in

the literature that specifically measure and index the sustainability of natural fiber crops. The construction of a novel framework for natural fiber evaluation, as proposed in this paper, seeks to fill the gap that exists for appropriate models to assess the sustainability of natural fiber crop cultivation.

### **Evaluating the Sustainability of Natural Fiber Cultivation in the Southeastern Region**

Traditionally, U.S. farmers rely on tools, models, and resources from governmental agencies, like state-based departments of agriculture, cooperative extension services, and agricultural technology companies, to provide an empirical framework that evaluates crop planning decisions and production systems design. These data-driven, computer-generated decision support models (DSM) allow farmers to consider different production variables in order to evaluate the costs and benefits of particular cultivation scenarios (Mare & Mare, 2017). DSMs typically have a predominant focus on factors like nutrient management, economic returns, market opportunity, and production input requirements, such as agrochemicals, fertilizer, seeds, water, among others (Mare & Mare, 2017; Adekanmbi, Olugbara & Adeyemo, 2014; Lindbloom, Lundstrom, Ljung & Jonsson, 2017). Also, current, available DSMs are generally most-appropriate for commodity producers and model production of crops like soybeans, wheat, corn, and cotton. Thus, farmers producing non-commodity crops require decision-making frameworks that are tailored to their specialty crop production systems and that account for the factors that support sustainable social, economic, and environmental farming objectives. As suggested by Mare (2017), farmers seeking to enhance the sustainability of their agricultural system and output require DSMs that enable them to simultaneously consider social, economic, and environmental factors to define and implement strategies for sustainable production, profitability, and resiliency (Rose et al., 2016, Adekanmbi, Olugbara & Adeyemo, 2014).

**Decision Support Model for Natural Fiber Cultivation.** Decision-support models, like the spreadsheet-based 2018 Row Crop Comparison Tool from University of Georgia Cooperative Extension Service, provide economic analyses of production of cotton and other commodity crops (University of Georgia, Department of Agricultural & Applied Economics, 2018). Other tools, like the AgriSync mobile application, calculate returns on cultivation investment and advise on production decisions real-time (AgriSync, 2018). These tools exclusively consider economic variables rather than a holistic evaluation of social and

environmental crop performance to make holistic production decisions. While a plethora of DSMs exist, like those mentioned above, a new generation of these resources are required in order to: 1) tackle the multidisciplinary, sustainability approach to agricultural planning and assessment; 2) evaluate the cultivation of specialty natural fiber crop, and; 3) support farmers in environmentally-sound, resource-conserving, and socially-beneficial crop production, ensuring that the three dimensions of sustainability are upheld (Ikerd, 1993).

Therefore, the primary objectives of this paper were: 1) to construct an empirical framework to evaluate the cultivation of a variety of natural fiber crops in the southeastern United States, and; 2) to systematically rank the crops based on their performance against selected social, economic, and environmental criteria in a Natural Fiber Crop Sustainability Index. This resulting framework provides a foundation for a new kind of DSM for natural fiber crop evaluation.

### **Multicriteria Decision Analysis for Sustainable Agriculture Evaluation**

This evaluation model was constructed using a Multicriteria Decision Analysis (MCDA) methodology. MCDA applies a computational theory that systematically collects, synthesizes, and examines the multidimensional performance for each crop against the social, economic, and environmental criteria considered. Applied to the problem of determining the most sustainable natural fiber crop for production in the southeastern United States, the method assesses the sustainability of conventional cotton, flax, hemp, and organic cotton—four crops that have been historically, or are currently, produced in that region. The results of the evaluation generated an index of sustainability of the crops to guide on-farm decision-making and increase general knowledge of fiber crop production. (Montazar & Snyder, 2012; Stefanova, Arnaudova, Haytova, & Bileva, 2014; Kolios, Mytilinou, Lozano-Minguez, & Salonitis, 2016). Profiles for the four crops evaluated in this paper are located in Appendix A below.

MCDA has been applied extensively to sustainable agricultural research problems in order to model and evaluate options that support sustainable production decisions. Utilizing MCDA, Montazar and Snyder (2012) determined ideal cropping pattern planning for an irrigation district under water scarcity in Iran. Another study assessed the sustainability of various cropping systems and implications for using MCDA (Sadok et al., 2008). Accordingly, in research specific to Bangladeshi agriculture, MCDA was utilized by Palash and Bauer (2016) to make sustainable land use decisions on rice versus fish farming cropping systems. Ramirez-

Garcia, Carillo, Ruiz, Alonso-Ayuso and Quemada (2015) applied a MCDA to determine the crop suitability for cover crops and cultivar species.

Specific to the selection of the most sustainable crop for production: Cobuloglu and Buyuktahtakin (2015) used a MCDA to select the most sustainable biomass crop for biofuel production in Kansas; Agha, Nofal, and Nassar (2012) analyzed crop planning in the Gaza strip using a MCDA, and; and Pozderec, Bavec, Rozman, Vincec, and Pazek (2015), utilized a MCDA to assess sustainable cultivation of commercially attractive vegetables in Galicia, Spain.

**PROMETHEE: A Methodology to Analyze for Natural Fiber Cultivation.** The literature described above spans a variety of MCDA methodologies applied. For this specific project, the MCDA methodology selected was the Preference Ranking Organization Method for Enrichment Evaluations (PROMETHEE). PROMETHEE is based on comparative computations of each crop's performance for each criterion against the performances of the other crops. The better the crop's performance, the higher its resulting score is on a normalized scale from 0-1. These scores determine a ranking from "most-to-least sustainable" based on the crop's aggregate score (Cinelli, Coles & Kirwan, 2014). The inspiration for the selection of PROMETHEE for this paper's natural fiber crop analysis was a paper from Kylili, Christofourou, Fokaidis, and Polycarpou (2016), which used PROMETHEE to determine most appropriate energy crop for exploitation in Cyprus.

The paper by Kylili, Christofourou, Fokaidis, and Polycarpou (2016) focused on the importance of biomass energy crops to meet carbon reduction targets and increase national energy security. The authors used PROMETHEE "to indicate the most optimal energy crops for cultivation in Cyprus according to the performance ranking of the energy crops" (Kylili, Christofourou, Fokaidis & Polycarpou, 2014). The authors evaluated six potential crops (sweet sorghum, sugar beets, maize, barley, potato, and wheat) against the five criteria considered most important to Cypriot farmers, as determined through surveys and interviews (irrigation demand, fertilizer demand, production yield, labour, energy plant calorific value) (Kylili, Christofourou, Fokaidis & Polycarpou, 2014).

The research expounded upon in this paper also employs PROMETHEE in a similar manner as Kylili, Christofourou, Fokaidis, and Polycarpou to index crops according to sustainability criteria within a particular region. The two scenarios included in this paper evaluated and indexed two sets of natural fiber crops produced in the southeastern United States



based on their overall sustainability performance: 1) conventional cotton, flax, hemp, and organic cotton, and; 2) the alternative natural fiber crops flax, hemp, and organically-produced cotton.

### **Research Methods**

The primary objective of this research was to construct a novel empirical model in order to analyze two sets of natural fiber crops that are readily adaptable for production in the southeastern United States. The model established an index for these crops based on the computation of a Net Sustainability Score for each alternative crop. As discussed in the Introduction above, farmers seeking to take advantage of the opportunity to grow natural fibers must simultaneously consider a number of social, economic, and environmental impacts. Therefore, Multicriteria Decision Analysis (MCDA), as introduced in the preceding sections, was the approach selected for the evaluation because it could systematically collect, synthesize, and examine a set of fiber crops against a number of sustainability criteria (Montazar & Snyder, 2012; Stefanova, Arnaudova, Haytova, & Bileva, 2014; Kolios, Mytilinou, Lozano-Minguez, & Salonitis, 2016).

### **Visual PROMETHEE Software**

This research applied PROMETHEE MCDA ranking methodology to determine how the two sets fiber crops investigated in this study compare to one another against a set of social, economic, and environmental criteria. Using the PROMETHEE results, each crop's Net Sustainability Score, was then used to construct the Sustainable Fiber Crop Preference Index. In this index each crop was ranked in descending order by their respective Net Sustainability Score, with the highest score indicating the most sustainable crop.

The fiber crop evaluation matrix was built in the software Visual PROMETHEE, which provided useful graphical representations of the analysis' results. The steps to build the Visual PROMETHEE evaluation matrix are as follows, and are represented visually in Figure 1:

- 1) Define the objective and scenarios: The objective was to construct a sustainability index of natural fiber crops produced in the southeastern United States.
- 2) Define the crop alternatives: The crops modeled included conventionally-produced cotton, flax, hemp, and organically-produced cotton

- 3) Define the sustainability criteria: The social, economic, and environmental criteria selected for evaluation derived from a literature review of indicators that measure the sustainability of agricultural systems.
- 4) Define preference parameters: The preference parameters to be defined by the evaluator were the maximization or minimization of, the selection of a preference function and indifference and preference thresholds. PROMETHEE preference parameters are explained in detail in the following Preference Parameter Definition section.
- 5) Define criterion weighting: Equal weighting for all criteria was used in this model and is detailed below in the following Preference Parameter Definition section.

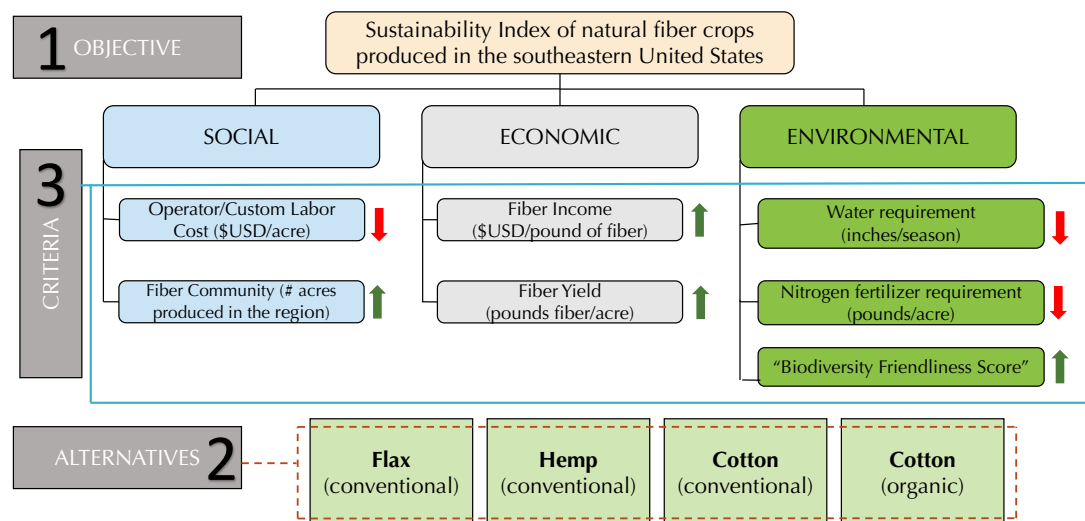


Figure 1. PROMETHEE process flow diagram.

### The Spatial Boundary Delineation: The Southeastern United States

This analysis focused on the production of natural fiber crops that are adaptable to cultivation in the southeastern region of the United States. This geographic boundary was delineated by the United States Department of Agriculture’s Natural Resources Conservation Service and is illustrated in Figure 2 below. As available crop production data were collected, the boundary was further refined to include just Kentucky, North Carolina, South Carolina, and Tennessee. These states were selected because historic and current cultivation data for the natural fiber crops was most available from production in these states through the United States

Department of Agriculture, state departments of agriculture in the region, and from research universities for the three natural fiber crops under consideration.

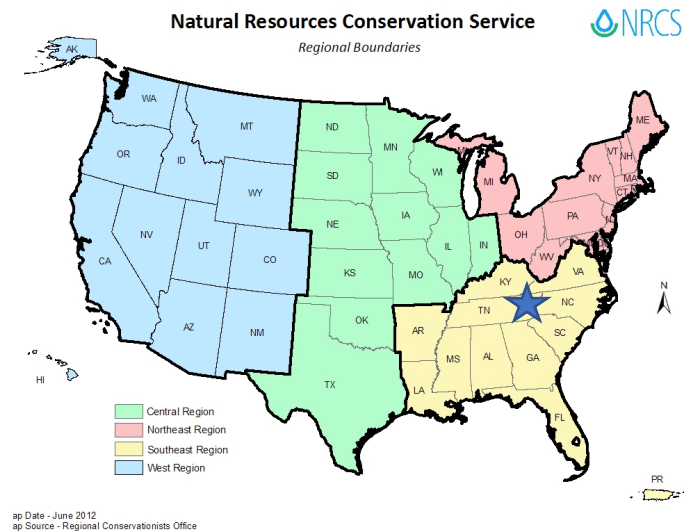


Figure 2. NRCS regional boundaries map. Reprinted from *Natural Resources Conservation Service*, by United States Department of Agriculture, Natural Resources Conservation Service, 2012. Retrieved from <https://www.nrcs.usda.gov/>.

Cotton cultivation, in both conventional and organic systems, is still heavily concentrated in the American southeast, as nearly 36% of the country's total acreage in cotton production is located in this region (United States Department of Agriculture, National Agricultural Statistics Service, 2017).

Records of hemp cultivation in the United States date back to 1606, with production later concentrated in Kentucky until its classification as a Schedule I narcotic in 1970 (Cherney & Small, 2016). Currently, extensive research is being conducted by universities, state departments of agriculture and farmers in Kentucky, North Carolina, and Tennessee to determine the viability of hemp cultivation of regionally appropriate cultivars. These research production plots accounting for over 17% of total hemp acreage planted to date in the United (Vote Hemp, 2018).

Finally, reports of flax production date back to Colonial America where flax was cultivated for fiber in nearly every colony (United States Department of Agriculture, Agricultural Marketing Resource Center, 2018c). Today, flax production is nearly nonexistent across the United States, but, like hemp, research is being conducted on nearly 4,000 acres in North Carolina and South Carolina to explore the potential for flax fiber re-establishment in the region.

### **Natural Fiber Crop Selection**

The four crops evaluated in this PROMETHEE model include conventional cotton, flax, hemp, and organic cotton. These crops were selected because they are, or have historically been, successfully produced in the southeastern United States. An overview of each of the crops that were analyzed is available in detail in Appendix A below.

Additionally, the crops were selected because secondary data specific to crop production in the southeastern United States was available from reliable sources. These sources included reports from the United States Department of Agriculture (e.g.: United States Department of Agriculture, 2018), state-specific cooperative extension service resources (e.g. North Carolina State Extension, n.d.), and academic research from regional institutions, including actual crop trials results (e.g. Department of Agricultural Economics, University of Kentucky, 2013). The data collected represented a diverse variety of crop-specific data for each of the sustainability criteria utilized in the model.

Data for some crops were easier to obtain than for others. For example, there was an abundance of production data and research available on cotton because it is most widely-produced natural fiber in the United States (Fisher, 2006). Yet, data for hemp were much more limited in the literature and research, as hemp, like marijuana, is technically a *Cannabis* plant. All *Cannabis* species are classified as a Schedule I narcotic under the Controlled Substances Act (Department of Agricultural Economics, University of Kentucky, 2013). The same data collection issue occurred in the research on flax, as it is currently only very minimally produced in the region and across the country. Therefore, the hemp and flax data used in this study was mainly extrapolated from crop research plots and growth trials, rather than from actual farm production reports. A data table with values, data sources, notations on the use of any proxy data, and other data collection information is available in Appendix B.

### **Sustainability Criteria Selection**

A literature review of the criteria and indicators that have been used to measure the sustainability of cropping systems guided the selection of a set of indicators for inclusion in this research. The most frequently occurring criteria were compiled and two to three were selected per dimension of sustainability: the social, economic, and environmental realms. The selection of criteria was highly dependent on the availability of data from secondary sources; thus, the data collected ultimately dictated the final set of criteria selected. These criteria were renamed for this

research and units of measurement were defined, with conversion of secondary data to these units as required. A table of criteria included in this model, and a rationale for the selection of the criteria, is detailed in Appendix C.

The criteria selected for this model correspond to the three dimensions of sustainability. The criteria names and measurement units are detailed in Table 1 below.

Table 1

*Sustainability Criteria Used in the PROMETHEE Fiber Crop Analysis*

SOCIAL DIMENSION		ECONOMIC DIMENSION		ENVIRONMENTAL DIMENSION	
Criterion Name	Measurement Unit	Criterion Name	Measurement Unit	Criterion Name	Measurement Unit
Operator/Customer Labor Cost	\$USD/acre (converted to 2018 dollars)	Fiber Income	\$USD/pound of fiber (converted to 2018 dollars)	Nitrogen Fertilizer Requirement	Total pounds of synthetic Nitrogen fertilizer applied/acre
Fiber Community	Total number of acres produced in KY, NC, SC, and TN	Fiber Yield	Total pounds fiber produced/acre	Water Requirement	Total inches of water required/season
				Biodiversity Friendliness Score	Adapted from Montford & Small (1999), which derived a numerical score to each crop based on desirable ecologically-friendly qualities

**Preference Parameter Determination**

Once the set of crops and sustainability criteria were determined for evaluation purposes, Visual PROMETHEE required the evaluator to define preference parameters in order for the software to compute the Net Sustainability Scores and construct the Natural Fiber Crop Sustainability Index. PROMETHEE uses *Preference Functions* selected for each criterion in order to model deviations between the performance of one crop compared to every other crop. For example, the water requirement of flax versus the water requirement of hemp was compared in Visual PROMETHEE using the Preference Function selected for the Water Requirement criterion. The software used the Preference Function to compute a deviation between the Water Requirement criteria values for each crop and determined which one was preferred based the

*Indifference* and *Preference Thresholds* set for the Water Requirement criterion. The preferred crop received a higher resulting score in the evaluation, and the preferred crop was then compared to all other crops against their Water Requirement values. Subsequent comparisons occurred in the same manner for all other criteria.

The Indifference Threshold used to determine the preference in comparisons of crops is defined as the largest deviation between the comparison of two crops considered negligible by the evaluator. The Preference Threshold is the smallest deviation required in the comparison to generate a full preference for one crop over another crop. Additionally, the evaluator was required to input specific weighting values assigned to each criterion, which may indicate the relative importance of each criterion as compared to the others. Finally, when these preference parameters were defined in Visual PROMETHEE, the software modeled the deviations between each crop, and expressed them as degrees of preference, or *Preference Scores*, normalized on a scale from 0-1. A Preference Score of 0 indicated a weak preference, while a Preference Score of 1 indicated the strongest preference for one crop over another in the analysis (Visual PROMETHEE, 2013). Additional information PROMETHEE's computational theory is detailed in Appendix D.

#### ***Zero-max Preference Parameter Methodology for Functions and Thresholds.***

Mladineo, Jajac, and Roguli (2016) developed a simplified preference parameter definition methodology for PROMETHEE evaluations called *Zero-max*. This method required that the Preference Function was set to Type V (Linear) of the six types of functions for each criterion. The Indifference Threshold in this method was set to zero for each criterion. The Preference Threshold was set to the maximal difference between the crop values for each criterion (i.e.: under the Synthetic Nitrogen Fertilizer Requirement criterion, organic cotton's value is the lowest at 0 pounds/acre, and flax's value is the highest at 60 pounds/acre. Subtracting the lowest value from the highest value gives the maximal difference to be used for that criterion's Preference Threshold). For the purposes of this research, this simplified Preference Function and Threshold method was applied to all criteria under evaluation.

**Equal Weighting for Sustainability Criteria.** The PROMETHEE methodology allows the evaluator to assign weights to each criterion as a measure of how important a particular criterion is with respect to the other criteria (Visual PROMETHEE, 2013). Weighting criteria is

useful when it is representative of the goals of the evaluator. For instance, when the economic potential of crop production is the most important objective, the evaluator can choose to apply more weight to that criterion over the others in the model, and the crops with the highest revenue per unit would then be ranked higher. Weighting criteria is often subjective, as it depends on the goals and/or opinions of the evaluator creating the model. In other research that applied PROMETHEE to crop selection, surveys of farmers were used in order to determine appropriate weights for criteria based on farmer responses (Kylili, Christofourou, Fokaides, & Polycarpiou, 2014). This paper's PROMETHEE model applied an equal weighting to each criterion, as farmers were not engaged in this study and, therefore, the evaluator could not objectively assign a specific weight that would be appropriate.

While an equal weighting method was employed in this evaluation, sensitivity analyses was included as part of the research methodology in order to check the strength of the results. Sensitivity analyses are used to the robustness of analysis results by manipulating input parameters (like the weight of criteria in the PROMETHEE model) to determine how they might change the result (the rankings of the fiber crops). The sensitivity analyses were applied using Visual PROMETHEE software tools which allowed for the weighting of criteria in the program's evaluation matrix to be modified. Manipulating the weighting of the criteria within each dimension of sustainability, revealed how the overall Natural Fiber Crop Sustainability Index results changed as more or less weight was given to particular criteria.

### **Research Assumptions**

This paper assumes that the data utilized in the model are representative of actual production of these fiber crops in the southeastern United States. Because the data was mined from reliable secondary sources from within the study region, it can be reasonably implied that the data points are appropriate proxies for fiber crop cultivation within the general spatial boundary. A caveat for this assumption is that farm-level specific requirements, due to climactic, soil, or other environmental conditions, vary widely, even within a particular geographic boundary. Thus, this model should be considered a general evaluation and benchmarking tool to assess the sustainability of fiber crops produced in the southeastern United States, rather than a practical index for a particular farm system's crop planning and production in that region.

A further premise of this paper is that scaling up hemp production is a viable option for farmers in the United States. Since 1970, hemp has been classified as a Schedule I narcotic under

the Comprehensive Drug Abuse Prevention Act (Controlled Substances Act [CSA]) because of its relation to psychotropic marijuana, also a member of the Cannabis plant species. As a result, hemp production is tightly controlled by the United States Drug Enforcement Agency (DEA). Currently, hemp cultivation requires a permit from the DEA and extensive security requirements; however, since 2014, farmers have been allowed to grow hemp under the jurisdiction of state departments of agriculture and universities. Over 25,000 acres of hemp are currently in production in 19 states (Vote Hemp, 2018). Successful legislation in 40 states has classified hemp as an agricultural crop distinct from marijuana. Furthermore, a current bipartisan effort in Congress seeks to remove hemp from the CSA, allow widespread cultivation across the country. This deregulation would place hemp, as an agricultural crop, under the jurisdiction of the United States Department of Agriculture. For these reasons, production of hemp was considered to be a feasible option for farmers; thus, the crop was included in the evaluation.

### **Results and Discussion**

After the crop data for each criterion was entered into the Visual PROMETHEE software matrix and preference parameters were defined, the results of crop comparisons were aggregated as Net Sustainability Scores which determined the overall ranking of the Natural Fiber Crop Sustainability Index. The natural fiber crop with the highest Net Sustainability Score was deemed to be the most sustainable crop for cultivation in the southeastern United States. The following section details the results of this PROMETHEE analysis.

#### **PROMETHEE Evaluation of Conventional Cotton, Flax, Hemp, and Organic Cotton**

The first group of natural fiber crops examined in Visual PROMETHEE included conventional cotton, flax, hemp, and organic cotton, as these four crops are currently produced, in the study's geographic boundary. The crop data collected for each criterion was entered into the Visual PROMETHEE evaluation matrix and the preference parameters were defined as discussed in detail in the Preference Parameter Definition sections. The four-crop Visual PROMETHEE evaluation matrix is located in Appendix E.





The Visual PROMETHEE software indexes the crops according to their sustainability performance based on the positive (Phi+), negative (Phi-) and net (Phi) preference flows that result from the software's ranking computations. For the purpose of clarity in this paper, the Phi net flow score will be referred to as the *Net Sustainability Score* and Phi+ and Phi- will be



referred to as the *Positive Sustainability Score* and *Negative Sustainability Score*, respectively. The *Sustainability Scores* take into account the performance of each crop against all criteria and express the preference for each crop on a scale between -1 to 1 (Kocmanova, Docekalova, & Lunacek, 2013). As described by Kocmanova, Docekalova, and Lunacek (2013) the Positive Sustainability Score conveys the strength of the crop in criteria comparisons, and how much it is preferred, as compared to the other crops, overall. The Negative Sustainability Score articulates the weakness of the crop's performance as compared to the other crops, or the extent to which the crop is dominated by the performances of the other crops. The Net Sustainability Score represents the balance of the Positive and Negative Sustainability Scores flows as a single net score. After applying the Visual PROMETHEE analysis, the four crops were indexed by their Net Sustainability Scores, as listed in Table 2 below.

Table 2

*Natural Fiber Four-Crop Analysis: PROMETHEE Flow Table I*

Rank	action		Phi	Phi+	Phi-
1	Conventional Cotton		0.0940	0.2982	0.2041
2	Hemp		0.0199	0.2654	0.2454
3	Flax		-0.0364	0.2241	0.2605
4	Organic Cotton		-0.0776	0.2227	0.3003

Ranking first in the resulting index was conventional cotton, followed by hemp, organic cotton, and flax. Though this analysis produced positive Net Sustainability Scores for conventional cotton (0.0940) and hemp (0.0199), these scores were within 0.07 of each other, expressing a very narrow margin of preference for conventional cotton over hemp. Further, the negative Net Sustainability Scores for organic cotton (-0.0364) and flax (-0.0776) indicate that, while conventional cotton and hemp technically outperform them on all criteria, the difference between the Net Sustainability Scores for conventional cotton and flax was just 0.17. Because all four crops expressed very close Net Sustainability Scores at nearly 0, it can be concluded that the difference in overall sustainability between the crops is negligible and crops are nearly identical in terms of their sustainability ranking.

Additionally, relying on the results from the weak four-crop analysis reinforces the current production status of conventional cotton in a region where this crop is grown in intensified monocrop systems (United States Department of Agriculture, 2018). Using the result from this analysis to promote conventional cotton as the most sustainable fiber crop for the

region diminishes opportunities for producers to diversify their agricultural systems with alternative natural fiber crops like flax, hemp, and organic cotton. Accordingly, this analysis was then expanded to evaluate just the three alternative natural fiber crops included in this study: flax, hemp, and organic cotton. The results of the three-crop analysis are available below.




**PROMETHEE Evaluation of Flax, Hemp, Organic Cotton**

The data collected for flax, hemp, and organic cotton were unchanged in the alternative natural fiber crop analysis. The preference parameters were recalculated to fit that set of data, using the Zero-max method detailed in the Research Methods section (Preference Parameter Determination). The Visual PROMETHEE evaluation matrix for the analysis of the alternative natural fiber crops is available in Appendix F.

After applying the Visual PROMETHEE analysis, the three crops evaluated were indexed by their Net Sustainability Scores, as listed in Table 3 below. Hemp was ranked as the most sustainable crop, followed by flax and organic cotton. This index differed from the results of the four-crop analysis above. First, hemp expressed a positive Net Sustainability Score of 0.1523, which is higher than the top Net Sustainability Score in the three-crop analysis for conventional cotton (0.0940). Secondly, the Net Sustainability Score for flax was 0.0004, which is an average result. While organic cotton received a negative Net Sustainability Score of -0.1528, the maximal difference between the top-ranked (hemp) and bottom-ranked (organic cotton) crops differed by a margin of 0.31, which is double the value of than the maximal difference between the crops that ranked first and last in the four-crop analysis.

Table 3

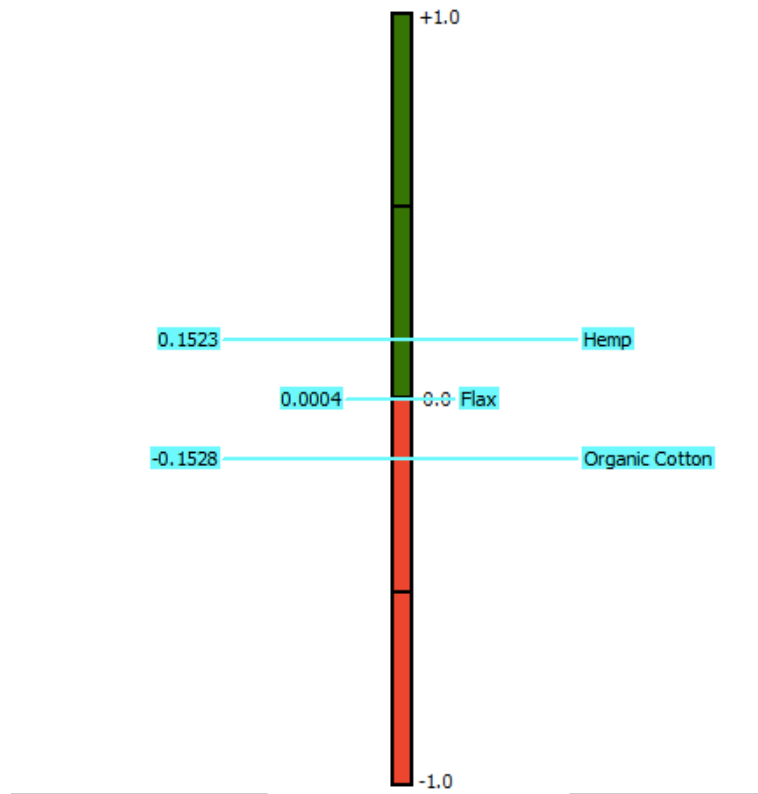
*Natural Fiber Three-Crop Analysis: PROMETHEE Flow Table II*

Rank	action		Phi	Phi+	Phi-
1	Hemp		0.1523	0.3811	0.2287
2	Flax		0.0004	0.2920	0.2915
3	Organic Cotton		-0.1528	0.2551	0.4078

In addition to computing Net Sustainability Scores in order to determine the optimal crop and index of all alternatives, the Visual PROMETHEE software provides visualizations to illustrate the results and aid the evaluator in understanding them. The following sections provide

explanations of the software's graphical output that are most pertinent to showcasing the results of the evaluations and visualizations of the resultant index.

**The PROMETHEE Rankings.** The PROMETHEE II Complete Ranking and PROMETHEE Diamond outputs from the software in Figures 3 and 4 illustrate the overall ranking of the crops based on the computation of the Net Sustainability Scores. These Scores are represented on the green and red vertical axis. As stated, hemp is the top-ranked crop in this evaluation, with an associated positive Net Sustainability Score. Flax is ranked second, with a Net Sustainability Score about 0. Organic cotton is ranked third with a negative Net Sustainability Score.



*Figure 3.* Visual PROMETHEE II complete ranking output.

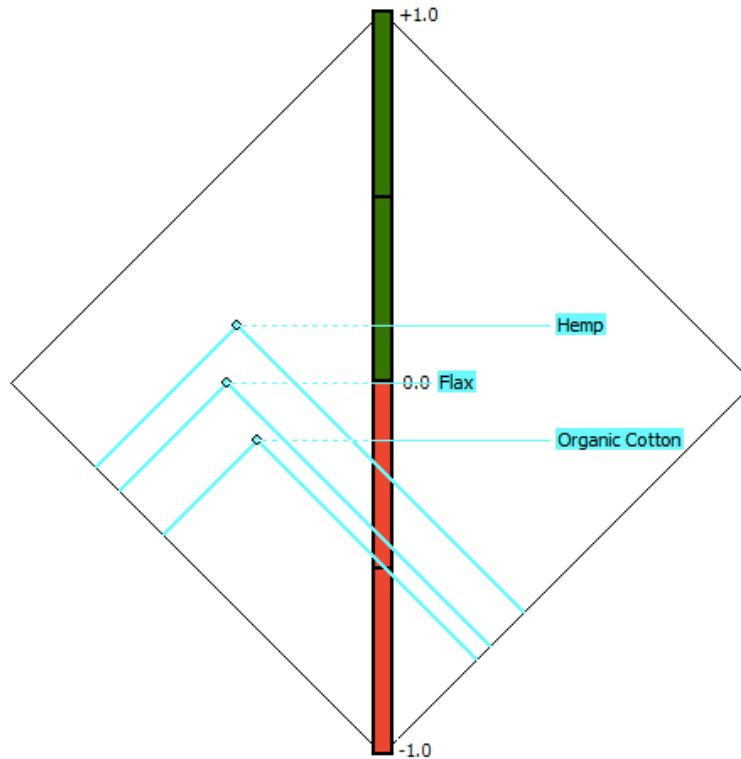


Figure 4. Visual PROMETHEE diamond output.

### The PROMETHEE Rainbow

The PROMETHEE Rainbow visualization is a simple bar graph, with the crop types displayed in order of most- to least- sustainable identified on the x-axis and the crop's Net Sustainability Score on the y-axis, as in Figure 5 below. The criteria "slices" that compose each crop's bar are "proportional to the contribution of one criterion (flow value times the weight of the criterion)" to the Net Sustainability Score (Visual PROMETHEE, 2013). The slices are color-coded according to the grouping of the criteria per dimension of sustainability. In this analysis, blue slices represent social criteria, grey slices indicate economic criteria, and green slices illustrate environmental criteria.

The slices listed above the x-axis correspond to the criteria within each sustainability dimension on which the crop performed best in the evaluation, which contributed to its Positive Sustainability Score. The slices below the x-axis are indicative of the criteria on which the crop performed weakly in the evaluation, constituting the Negative Sustainability Score. The balance of these slices is equal to the Net Sustainability Score plotted on the y-axis of this graph. As represented in the chart in Figure 5, hemp's performance on social and environmental criteria

contributed to its top-ranked position, while its economic performance negatively impacted its overall Net Sustainability Score. Flax's social and economic performances contributed to its resulting positive score, while its environmental performance had a negative impact on crop's overall score. Organic cotton's score was negatively impacted by its performance on social criteria, and positively affected by the crop's performance on environmental and economic criteria.

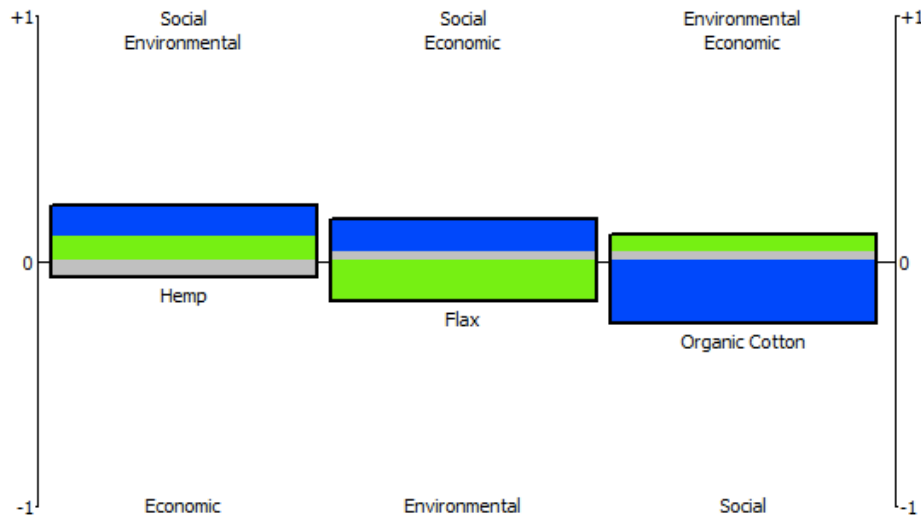


Figure 5. Visual PROMETHEE rainbow output.

The bar chart in Figure 6 provides a more detailed analysis of the contributions of each crop's performance against each specific criterion. The criteria that contributed positively to hemp's overall *Net Sustainability Score* were: Water Requirement (environmental), Community (social), Biodiversity Friendliness Score (environmental), Labor Requirement (social). The criteria hemp performed weakest on, which contributed negatively to hemp's Net Sustainability Score, were: Yield (economic), Income (economic), Nitrogen Fertilizer Requirement (environmental). Interestingly, the PROMETHEE Rainbow showed that flax and organic cotton are nearly incomparable in this analysis. Flax performs best on Yield, Labor Requirement, and Community; the three criteria for which organic cotton performed worst. The additional contribution of Water Requirement to organic cotton's *Negative Sustainability Score* prevents a full incomparability between the two crops.

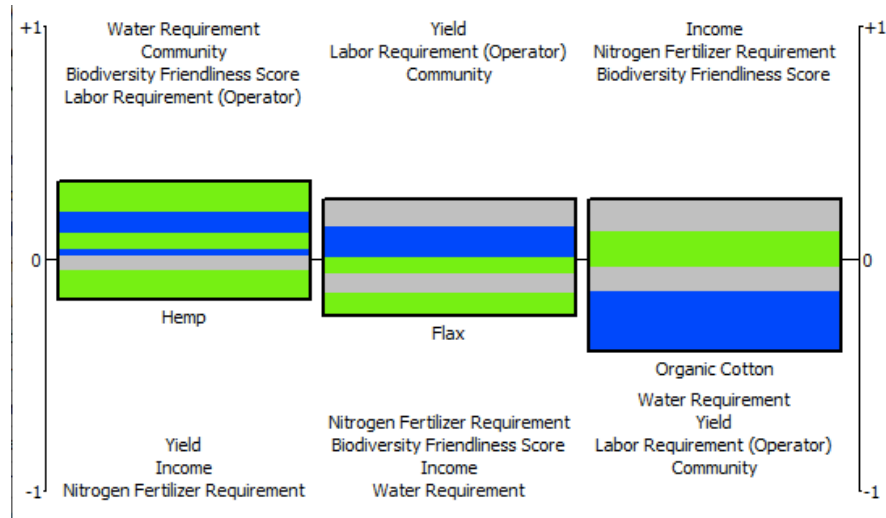


Figure 6. Visual PROMETHEE rainbow output by criterion.

### Sensitivity Analyses

Robust sensitivity analyses of this evaluation were conducted using a tool available in Visual PROMETHEE. The software's Walking Weights feature provided a visualization of the ranking of each crop by Net Sustainability Score similar to the PROMETHEE Rainbow output. The alternative natural fiber crops are listed in order from most- to least- sustainable along the x-axis and the crops' Net Sustainability Scores are plotted on the y-axis, as in Figure 7. The slices are color-coded according to the sustainability grouping of the criteria with social criteria in blue, economic criteria in grey, and environmental criteria in green. The sensitivity analysis was performed using the aggregate groupings of sustainability criteria rather than by individual criterion: i.e.: social criteria, as a whole, can be manipulated, but Labor Requirement and Community criteria within that group could not be changed individually in this type of sensitivity analysis. Other tools in Visual PROMETHEE allow sensitivity analyses of individual criteria.

Altering the weighting for each grouping of criteria allowed the evaluator to interpret how alternative weighting can impacted the results of the analysis. In the initial three-crop analysis, equal weight was given to each criterion (14% per criterion) in the evaluation matrix in order to produce a Natural Fiber Crop Sustainability Index. Figure 7 provides the Walking Weights visualization and the subsequent rank ordering by Net Sustainability Score. The environmental criteria group is weighted at 43% and the social and economic criteria groups are weighted at 29% because the environmental group has three criteria weighted at 14% within in,

compared to the two criteria in the social and economic groups. When the criteria groupings' weights were changed the Natural Fiber Crop Sustainability Index results varied considerably. The following sections provide more information on the results of the sensitivity analyses.

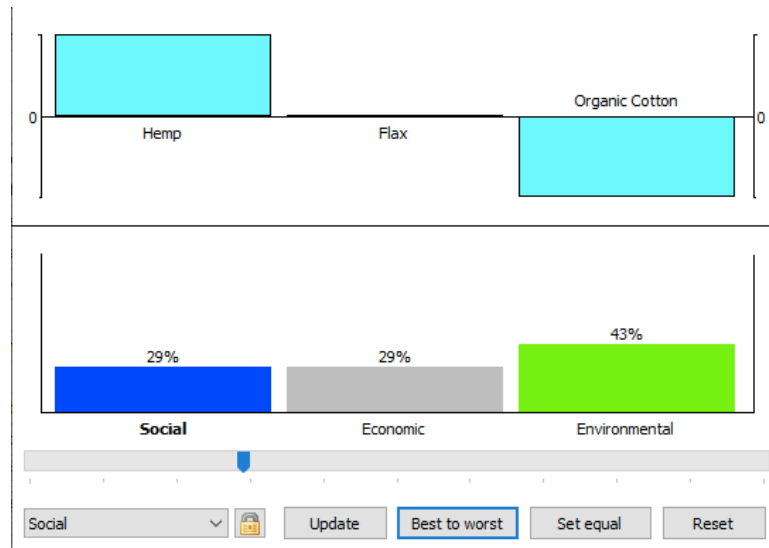


Figure 7. Visual PROMETHEE walking weights output.

**Social Criteria Sensitivity Analysis.** The PROMETHEE Rainbow indicated that hemp performed strongly on the social criteria selected for the analysis. However, when the weight of the social criteria grouping was modified, the order of crops in the index was changed. Table 4 below summarizes the changes in the rank ordering of the crops in the index as the social criteria weighting changed. The Visual PROMETHEE Walking Weights charts for the social criteria sensitivity analysis are available in Appendix G.

In short, hemp ranked as the first or second crop in the index when the social criteria are set at any weight. The most notable ranking variation occurred when the weights of economic and environmental criteria were kept equal, but social criteria were weighted less than or equal to 6%, which resulted in organic cotton as then being the top-ranked crop. From this result, it can be deduced that when social criteria are weighted less than other criteria, organic cotton outranks the other crops due to its stronger performance on economic and environmental criteria. When the weight of the social criteria was greater than or equal to 7%, hemp was the top-ranked crop until weighting was increased above 87%. At weightings from 88%-100% flax remains in the first position from and hemp returned to second position.

Because hemp remained in the top ranked position in the index for such a wide range of weighting for the social criteria, it is clear that hemp’s relatively strong social performance was an important contribution to its overall positive Net Sustainability Score. It can also be deduced that if social criteria were not included in the analysis, organic cotton would have a higher overall Net Sustainability Score, and if social criteria were the only ones included in the evaluation, flax would have a higher overall Net Sustainability Score due to the results of this analysis.

Table 4

*Social Criteria Weighting Sensitivity Analysis*

<b>Weight of Social Criteria Group in Three-Crop Analysis</b>	<b>First-ranked crop</b>	<b>Second-ranked crop</b>	<b>Third-ranked crop</b>
0%-6%	Organic cotton	Hemp	Flax
7%-87%	Hemp	Organic cotton	Flax
88%-100%	Flax	Hemp	Organic cotton

**Environmental Criteria Sensitivity Analysis.** The sensitivity analysis also revealed that, overall, hemp performed best when environmental criteria are weighted more than other criteria. In opposition to the sensitivity analysis on social criteria, flax, which performed best when social criteria were set at higher weighting, performed best when environmental criteria are set at lower weighting. Organic cotton never reached a top-ranked position when environmental criteria were set at any weighting but moved to second-ranked at a wide range of weighting from 56-100%, which indicated organic cotton has a relatively strong overall environmental performance. Table 5 summarizes the results of the environmental criteria sensitivity analysis. The Visual PROMETHEE Walking Weights charts for the environmental sensitivity analysis are available in Appendix H.

As in the sensitivity analysis for social criteria, hemp ranked as the first or second crop in the index when the environmental criteria were set at any weight. When the weight was set at 0-23%, flax ranked first in the index; therefore, it is clear flax performed worst on environmental criteria, as it is only top-ranked when this grouping’s weight was relatively low. Hemp ranks first when the criteria weights range from 24%-100%, which indicated its strong performance and the contributions its environmental characteristics make to its overall top-ranking in the final Natural Fiber Crop Sustainability Index.



Table 5

*Environmental Criteria Weighting Sensitivity Analysis*

<b>Weight of Environmental Criteria Group in Three-Crop Analysis</b>	<b>First-ranked crop</b>	<b>Second-ranked crop</b>	<b>Third-ranked crop</b>
0%-23%	Flax	Hemp	Organic cotton
24%-55%	Hemp	Flax	Organic cotton
56%-100%	Hemp	Organic cotton	Flax

**Economic Criteria Sensitivity Analysis.** When the weighting of the economic criteria grouping was changed in the sensitivity analysis, it revealed that hemp's performance varied most on these criteria. This result is supported by hemp's weak performance on economic criteria in the PROMETHEE Rainbow visualization. Table 6 provides a summary of the economic criteria sensitivity analysis results. The Visual PROMETHEE Walking Weights charts for the economic criteria sensitivity analysis are available in Appendix I.

Table 6

*Economic Criteria Weighting Sensitivity Analysis*

<b>Weight of Economic Criteria Group in Three-Crop Analysis</b>	<b>First-ranked crop</b>	<b>Second-ranked crop</b>	<b>Third-ranked crop</b>
0%-18%	Hemp	Flax	Organic cotton
19%-63%	Flax	Hemp	Organic cotton
64%-100%	Flax	Organic cotton	Hemp

One particularly interesting outcome of this analysis is that flax was top-ranked when economic criteria were set at a range of 19-100%. Thus, flax performed very strongly on economic criteria. When the weights of economic criteria were set at higher values, flax's overall rank position was improved. Alternatively, hemp was negatively influenced by its performance on economic criteria in this analysis and was ranked first only when economic criteria weights were set at less than or equal to 19%. At higher weights, greater than or equal to 64%, hemp is ranked third in the index for the first time in the analysis, which further underscores its poor performance on economic criteria.

**Discussion of Sensitivity Analyses.** The sensitivity analyses provided interesting insight on the results of this evaluation and the influences on the ranking of the Natural Fiber Crop Sustainability Index. First, organic cotton never outranked either hemp or flax when weighting was modified on any criteria groups, which supports the initial result that organic cotton is the third-ranked crop. Secondly, even though hemp was top-ranked in the evaluation results, the sensitivity analyses reveal that hemp was actually outperformed at a number of weightings of particular criteria by flax. Thirdly, flax outranked hemp when social and economic criteria were considered the most important. Thusly, it can be deduced that if a farmer wanted to produce crops with the highest social and economic returns, and weighted these criteria highest, she should select flax for cultivation. If a farmer was seeking to grow a fiber crop with the best environmental performance, she should select hemp, because it was the top-ranked crop at the widest range of weights.

However, because this evaluation held all criteria equally, hemp, which was top-ranked for the widest range of weights on social and environmental criteria, is considered the most-sustainable crop in the analysis. Unless flax's social and environmental performances can improve, it will not outrank hemp in an equal weighting evaluation. Yet, the usefulness of PROMETHEE is that weighting of criteria can be so easily modified, which can produce very different results, as evidenced in this sensitivity analysis, to meet particular objectives of specific evaluators.

### **Recommendations for the Re-establishment of Hemp Cultivation in the United States**

The results of this PROMETHEE evaluation indicated that hemp is the most sustainable crop alternative natural fiber crop to be pursued for production by farmers in the southeastern United States. Consequently, this result required an examination of the feasibility of hemp production in the United States. This analysis illuminated the barriers to scaling up cultivation in the study region. The sections below include: a review the multidimensional sustainability benefits of hemp; a discussion of the main barriers for full exploitation of the crop, and; recommendations for overcoming these barriers for commercial cultivation.

### **The Multidimensional Benefits of Hemp Fiber Cultivation and Use**

The outcome of this research, wherein hemp was ranked as the most sustainable fiber crop adapted to cultivation in the southeastern United States, is supported by vast literature that

purports hemp's social, economic, and environmental benefits. Hemp is a useful natural fiber in textile applications, and offers reduced externalities associated with products it is a component of, such as: bioplastic composites, biofuel, plant-based protein foods, cosmetics, paper, construction material (Smith-Heisters, 2008). While hemp can be cultivated for seed or fiber, hemp is readily adaptable for dual cropping of cultivars with different purposes, in both conventional and organic production systems (Smith-Heisters, 2008). A Canadian study found that a system of dual-cropped hemp produced 700 pounds of grain, 530 pounds of seed meal, and 1,300 pounds of fiber (from 5,300 pounds of straw) (Smith-Heisters, 2008).

Hemp is considered to be a low-input and low-impact crop, naturally requiring no herbicides or pesticides because it is seeded and cultivated in high density stands that crowd out weeds and pests (Smith-Heisters, 2008; Kosolov, 2009). Hemp's branched roots system, reaching depths of 2.5 meters, can extract nutrients and take up groundwater, and have been found to have bioremediation effects on contaminated soils (Fine, 2014; Fortenbery & Bennett, 2015; Small & Marcus, 2002).

Hemp is useful in combatting climate change, as it efficiently sequesters larger amounts of carbon during photosynthesis than other crops; thus, the crop is a component of carbon off-setting programs in the United Kingdom (Kosolov, 2009). A life cycle assessment comparing emissions and resource use for all processes through harvest for seven crops in France, found production of a hemp fiber crop to have lower impacts on eutrophication, climate change, acidification, terrestrial ecotoxicity, and energy use than the others in the study (Smith-Heisters, 2008). Further, production of hemp, instead of cotton, indicates that herbicide, pesticide, fertilizer, and irrigation requirements needed for cotton cultivation can be reduced by half (Smith-Heisters, 2008). The use of hemp, instead of synthetic fibers, reduces energy inputs by six times (Smith-Heisters, 2008).

In warmer climates with adequate rainfall, like the southeastern United States, hemp can produce multiple harvests per year; therefore, it has great potential for economic returns as a cash crop and/or a cover crop (Smith-Heisters, 2008). As a result of its usefulness and adaptability, hemp has been grown in the southeastern United States for over 100 years. Specifically, in Kentucky, hemp production was well-established throughout the state beginning in 1606 and contributed to the expansion of textile production as the largest industry in the south through the mid-twentieth century (Cherney & Small, 2016; Hamlin, n.d.). Today significant research and

development investment is being directed to support the re-establishment of hemp production in southeastern states like Kentucky, North Carolina, and Tennessee.

### **Restriction of Hemp Cultivation in the United States**

As a result of hemp's sustainability traits, the hemp product market is growing. In 2016, the total retail value of hemp products sold in the United States was estimated at \$688 million; yet, the hemp used in these products was not grown in the United States (Cornell University, 2017). Rather, as a result of the current legal status of hemp in United States, the majority of hemp and hemp products are imported from Canada and China, two of the largest producers of fiber and seed, respectively (Cornell University, 2017; Cherney & Small, 2016). Currently, hemp and psychotropic marijuana, both derived from *Cannabis* plants, are classified as a Schedule I narcotic under the Controlled Substances Act. Consequently, been under the jurisdiction of the United States Drug Enforcement Agency (DEA) since 1970 (Kosolov, 2009). Yet, hemp is genetically distinct from marijuana as it contains less than 1% of the psychoactive chemical delta-9-tetrahydrocannabinol (THC), which is found in marijuana plants at concentrations ranging from 3%-20% (Kosolov, 2009).

As a result of its conflation with psychotropic marijuana cannabis, hemp production is tightly controlled in the United States; though, it is not illegal to cultivate hemp (Kosolov, 2009). Farmers are able to appeal to the DEA for permits to produce hemp, but are required to overcome expensive, impractical barriers to its production like extensive security measures and enforcement by the DEA (Kosolov, 2009). At present, the United States is the only developed nation that controls the cultivation of hemp, as the crop is currently cultivated for commercial use in 31 countries around the world (Johnson, 2018).

**Removal of Hemp's Schedule I Classification.** Section 7606 of The Agricultural Act of 2014 (the 2018 Farm Bill) permitted universities and state departments of agriculture to grow hemp with THC levels of 0.3% or less in the forty states where legislation has passed defining industrial hemp as distinct from marijuana and allowing for cultivation (United States Department of Agriculture, National Institute of Food and Agriculture, n.d.). Also, The Hemp Farming Act of 2018 was passed in the United States Senate with bipartisan support and has been included in the final version of the 2018 Farm Bill, which is likely to pass by the end of 2018 (Vote Hemp, 2018). This legislation removes of hemp from the controlled substances list

and moves regulation from the DEA to the United States Department of Agriculture (USDA), state departments of agriculture, tribal nations, and United States territories, in the same manner as other agricultural crops (S. 2667, 2018). The passage of The Hemp Farming Act would reduce the regulatory barriers to production and participation in the growing hemp market. However, other barriers to production must be addressed in order for American farmers to competitively produce industrial hemp at scale.

### **Additional Barriers to Hemp Production**

Federal deregulation of hemp a critical first barrier to overcome for widespread production of hemp; however, a survey of fiber producers in the southeastern United States and a report by Cornell University identified additional hurdles in the path of viable, full-scale hemp production, including access to: capital, seed, infrastructure, supply chains, and markets (Hamlin, n.d.; Cornell University, 2017).

**Investing in Domestic Cultivation.** Farmers in the southeastern United States stressed the importance of access to capital, including grants and low-interest loans, to purchase land, to expand fiber production, and to access new markets (Himes, n.d.). If adopted, the 2018 Farm Bill would move control of hemp cultivation under the jurisdiction of the USDA and state departments of agriculture. These entities could then allocate more funding to farmers seeking to diversify with or seize a new market opportunity through hemp production. For example, the state of New York is making up to \$10 million available to farmers to advance hemp research and economic development opportunities for hemp cultivation and products (New York State, n.d.). Alternatively, direct partnerships with brands seeking domestic hemp may offer opportunities for funding or better prices for production. Or, investment in innovative production structures, like farmer-owned hemp and/or fiber cooperatives, may provide innovative cost- and profit-sharing models that would allow farmer members to scale up as a fiber producing community.

**Establishing Sustainable American Seed Stock.** Investments in research and production must begin with the establishment of low-THC cultivars adapted to the various climactic regions in the United States. Because hemp production is regulated as a narcotic, the United States' seed supply has been essentially eliminated. Since hemp seeds must be imported,

farmers face rising input costs to access certified seed. The United States seed stock must be rebuilt through the development of regionally and specialized hemp breeds, maximizing for yield, genetic diversity, and sustainability traits. Species of wild hemp that grow throughout the country, known as “ditchweed”, could be used as a genetic basis for cultivar development, or adaptation of viable cultivars from Europe or Canada are possible genetic material for the development of hemp seeds for production in the United States (Smith-Heisters, 2008; Himes, n.d.).

**Advancing Regional Production Knowledge.** Because hemp production has been essentially halted by regulation for over 80 years in the United States, since the passage of the Marihuana Tax Act of 1938 which first put controls on any *Cannabis* cultivation, the national knowledge and resources for cultivation of, and development of production and processing for hemp extremely limited. Making hemp production educational materials and tools, university and governmental research resources, and technical and business assistance programs more widely available would provide support to hemp producers that seek to cultivate hemp or scale up hemp production.

Specific investments in hemp harvesting and processing technology would greatly reduce barriers for small and mid-scale farmers for whom expensive capital equipment and infrastructure investments are out-of-reach. Harvesting hemp is labor intensive because the crop is not suited to mechanized harvesting with traditional combine equipment as the stalks tend to wind around the components (Cornell University, 2017). Adopting the use of appropriate harvesting equipment from other hemp producing nations, like Canada’s utilization of baling and swathing implements, would provide a foundation upon which American farmers could begin to appropriately harvest the crop without damaging it (Cornell University, 2017). Additionally, farmers in the United States must work to streamline the crop’s production, harvesting, and fiber separation processing in order to compete with other hemp-producing countries who have already mechanized and automated these processes to support commercial production (Smith-Heisters, 2008).

**Strengthening American Supply Chains.** All members of the supply chain can strengthen the viability of hemp production in the United States by reestablishing regional textile systems and connecting farmers to textile artists, brands, fiber mills and suppliers. Investing in

regional processing is an essential step to supporting commercial-scale hemp production. Because raw hemp is a weighty crop, the cost of transporting it long distances to process is uneconomical for farmers (Kosolov, 2009). Analyses of the cost to grow, transport, and process hemp for fiber found that farmers would need to grow at least 50 acres of hemp within 80 kilometers of a processing facility to make the production and processing economics feasible (Cherney & Small, 2016; Hamlin, n.d.). Establishing regional processing facilities would reduce a transport burden from field to processor and would support the regional economy through jobs creation in hemp processing.

Currently, Sunstrand, is the sole hemp fiber processing facility located in the United States and is based in the southeastern region (Hamlin, n.d.). Utilizing Sunstrand's technology, coupled with developments in bast fiber processing for crops like hemp and flax from around the world, may help to reestablish additional facilities using advanced technology. Alternatively, the retrofitting of existing facilities, like cotton or animal fiber mills, could streamline the establishment of regional hemp processing facilities and hasten the domestic crop's entrance into the market (Smith-Heisters, 2009).

### **Recommendations to Improve PROMETHEE Use in Natural Fiber Crop Evaluation**

As stated in the Introduction, to the best of the author's knowledge this paper's use of a PROMETHEE evaluation to determine of the most sustainable natural fiber crop adapted for production in the southeastern United States was the first-of-its-kind application of this methodology to natural fiber crop analysis. Utilizing PROMETHEE analysis in this study to create a Natural Fiber Crop Sustainability Index for cultivation within a specific geographic boundary was an exercise that could help identify pathways of progress to overcome the diversity and challenges in sustainable fiber crop production (Craheix et al., 2015). This evaluation serves as a benchmark for future PROMETHEE analyses and fiber crop studies, as it can be easily manipulated to assess alternative cultivation scenarios of alternative fiber crops outside of the study's boundaries. The limitations of this specific PROMETHEE application, as well as recommendations to overcome them are detailed in the following sections.

**Overcoming the Limitations of the PROMETHEE Evaluation of Natural Fiber Crops in the Southeastern United States.** Limitations of this evaluation resulted from the narrow geographic scope and the use of secondary data sources which dictated which crops and

criteria were selected. In addition, the PROMETHEE methodology includes an inherent bias, as it was designed to model goals and objectives that are defined by the evaluator building the model. While these limitations constrict the overall results, steps were taken to overcome these barriers in the evaluation (Kylili, Christofourou, Fokaides, & Polycarpou, 2014).

First, the author selected alternative natural fiber crops for which production data were available from the southeastern United States where historic knowledge, experience, and some infrastructure to support re-establishment of these alternative fiber crops. Secondly, the evaluation criteria were obtained from a thorough literature review of sustainability criteria used to assess agricultural impacts, rather than just from the author's own personal choice of sustainability criteria important to her. Finally, the use of the *Zero-max* and equal weighting methodologies, coupled with the inclusion of the sensitivity analyses, served to reduce the fundamental subjectivity of the PROMETHEE evaluation and ensure robustness of the results.

**Expansion of the Spatial Boundary.** The limited spatial boundary used in this research allowed for regional production to be readily modeled, but it prevented the resulting Natural Fiber Crop Sustainability Index from being widely applicable to production in other regions of the United States. Instead, the results serve to support the construction of a theoretical index and heuristic approach to model sustainability performance of natural fiber crops using PROMETHEE. Expansion of the geographic scope, or an alternative delineation of the spatial boundaries into other agricultural production regions or zones, would require that the evaluator load data from within those locales into the PROMETHEE evaluation matrix. The use of geographically-specific data from within varied regions may produce alternative Sustainability Scores and resultant Natural Fiber Crop Sustainability Index in other analyses.

For example, if the foci were moved to the cultivation of organic cotton, flax, and hemp in California using the same sustainability criteria and preference parameters, the evaluator would need to perform associated PROMETHEE analysis of natural fiber crop production data specific to California and/or particular production systems. Potentially, such data could differ significantly due to variations in the social, economic, and environmental influences on agriculture between California and the southeastern United States. Further, variances in production systems, such as conventionally-produced versus organically-produced hemp, may result in different results in input use, yield, and market price, which could affect the results of the analysis and change the ranking of the crops in the index. Therefore, hemp might not rank as



most sustainable option for cultivation by farmers in California. Changes in the evaluation boundary may also allow for the inclusion of a wider variety of natural fiber crops in the analysis, or it could be useful for comparing the cultivation of natural fiber crops to other field crops, natural fibers, or agricultural products in order to best meet the farm production goals.

**Inclusion of Additional Natural Fiber Crops.** The expansion of the spatial boundary might permit the inclusion of additional varieties of natural fibers for evaluation depending on the cultivation conditions of the geographic scope of the PROMETHEE analysis. For example, in the southeastern United States, further research on bamboo and kenaf production could produce data that can be added to this PROMETHEE model for a broader evaluation of a wider array of natural fiber crops. Including more crop species might impact the results of the analysis and determine that hemp is not, in fact, the most sustainable natural fiber crop produced in the region. Fortunately, the PROMETHEE framework can be easily manipulated to expand or contract the number of crops under evaluation.

Additionally, PROMETHEE allows evaluators to widen the scope of natural fibers under analysis. PROMETHEE does not require that the natural fibers being examined in a single scenario be solely plant-derived. For organizations like Fibershed, which was referenced in the Introduction, working with farmers to establish and expand fiber production, PROMETHEE can be a useful method evaluate the production of natural fibers from a diversity of plant and animal sources on specific criteria. If evaluators seek to analyze the production of fibers from both crops and animals like sheep, rabbits, goats, llamas, and alpacas, PROMETHEE is able to handle this disparate data as long as the criteria used for evaluation are measurable for each fiber alternative included in the matrix.

**Modification of the Sustainability Criteria.** Typically, PROMETHEE modelers select the criteria included in the evaluation based on the data that are available and their overall goals and objectives. For example, if a farmer wants to determine which crop will provide the highest economic returns, she may consider evaluating crops based on criteria like: market demand, yield per acre, revenue per unit harvested, and production costs. However, because this PROMETHEE evaluation was not created for a specific farmer's goals, the sustainability criteria selected for inclusion in this analysis were drawn from a literature review of vetted indicators that are used to measure agricultural sustainability. Adding additional—or removing useless—

criteria could certainly impact any evaluation results, and this modification is accomplished easily in PROMETHEE analyses in order to test various scenarios.

Utilizing standard indicators for measuring agricultural sustainability as evaluation criteria helped to remove bias in this PROMETHEE evaluation. Yet, the final choice of criteria was dependent on the regional production data available for each crop. For instance, criteria like pesticide application rates, the use of heavy machinery versus the use of hand labor, input costs, market demand, and number of harvests per acre per year may provide more measures of the social, economic, and environmental sustainability of natural fiber crop production. Because this data was not readily available from the secondary sources referenced, these criteria were not tested and could not be included in the analysis. Future PROMETHEE evaluations could engage farmers and other natural fiber cultivation stakeholders via surveys or interviews might help to determine the criteria most germane to their objectives and realities of their production system. This technique was used by Kylili, Christofourou, Fokaides, and Polycarpou (2016) for the selection of sustainability criteria used to evaluate biomass crops in Cyprus.

### **Further PROMETHEE Evaluations of Natural Fiber Crops**

In addition to modifying the spatial boundaries, set of fibers, or sustainability criteria used in PROMETHEE evaluations of natural fiber production, future applications may consider using PROMETHEE's capacity to incorporate consensus decision-making with various stakeholders by integrating the PROMETHEE evaluation with a tool like Geographic Information Systems (GIS).

According to Visual PROMETHEE (2013), extensions of the methodology can facilitate negotiation and group decision making for multiple evaluators and stakeholders involved in a decision process. The software's ability to generate multi-scenario models can allow for immediate comparisons between outcomes, points of view, and can determine sources of disagreement for discussion in order to identify the best consensus decision.

For example, if a group of farmers in a cooperative ownership structure were seeking to cultivate natural fiber crops for a specific market, they would be able to build multiple PROMETHEE scenarios, each with specific preference parameters that support particular objectives, in order to compare options and then make a decision. Further, Visual PROMETHEE software can integrate geolocated data and results onto maps for additional analysis and decision-making about crop production siting.

Mladineo, Jajac, and Rogulj (2016) successfully integrated the opinions of multiple decision makers within PROMETHEE scenarios, and further represented the results using GIS. They deployed PROMETHEE to evaluate the opinions of mine action stakeholders—e.g. politicians, humanitarian organization leaders, and project managers—in order to set priorities for mine action. These mine action projects were then mapped by combining the results of PROMETHEE evaluations with GIS data in order to manage initiatives (Mladineo, Jajac, and Rogulj, 2016). As in the management of the Management of Mine Action Projects, the integration of PROMETHEE and GIS could be especially useful in agriculture for selecting the best location within a region or farm system for crop cultivation based on climate, soil health, rainfall rates, or other factors. Finally, mapping these production sites might help manage issues like upstream runoff of agrochemicals and fertilizers and other point- and non-point source pollution.

### **Conclusion**

The objective of this research was two-fold: 1) to analyze a set of four natural fiber crops that were adaptable to production in the southeastern United States using a series of social, economic, and environmental criteria, and; 2) to create a Natural Fiber Crop Sustainability Index using the results of the evaluation. The results of this analysis, and the process of creating the evaluation framework, served to provide farmers in the southeastern United States with a novel decision support model specifically tailed to natural fiber crop production in a sustainable manner.

The research employed applied the multicriteria decision analysis methodology, PROMETHEE, to perform pairwise comparisons of the crops against one another using each crop's performance per criterion included in the model. The PROMETHEE methodology was selected because it allowed for multiple criteria to be considered simultaneously as an aggregate score, rather than categorizing the crop by the performance per criterion. For example, flax performed best on the operator labor criterion, with the lowest cost per acre, while hemp performed best on the Biodiversity Friendliness Score criterion, as it had the highest score. Additionally, organic cotton performed best on the Fiber Income criterion, as it receives the highest price per pound, but conventional cotton performed best on the Fiber Community criterion, as this crop has the most acres in production within the southeastern United States region. Clearly, because some of the natural fiber crops perform best on select criteria over

others, it is difficult to select an optimal crop for production or index them according to their sustainability attributes.

Therefore, the use of PROMETHEE aids in generating a score based on the comparisons of each crop's performance per criterion against the others. The results of these comparisons generated Net Sustainability Scores that were ranked from highest to lowest in the final index. In the first PROMETHEE evaluation of conventional cotton, flax, hemp, and organic cotton, conventional cotton was top-ranked, but only very marginally ahead of hemp, flax, and organic cotton, respectively. The top-ranking of conventional cotton was due to the crop's strong performance on criteria like: Community, Labor Requirement, Water Requirement and Nitrogen Fertilizer Requirement. Because it is so heavily produced in the United States, the production of the cotton commodity crop has become so precise and calculated. Varieties of cotton are genetically-engineered to require less inputs, and labor has become mechanized to reduce costs.

Further, the Community criterion measured the total acreage produced in the southeastern region as an indicator of the farmer-to-farmer knowledge and resource sharing potential, and cotton acreage (950,000 acres) is 214 times larger than hemp, the crop with the next highest acreage (4,436). These factors contributed to cotton's ranking as most sustainable crop; however, the Net Sustainability Scores in this scenario were all nearly identical at about 0. The reliance on this weak result both perpetuates the monocropping of conventional cotton in the southeastern United States and does not provide a full analysis of the alternative fiber crops (flax, hemp, and organic cotton) that are not produced actively in the United States.

Accordingly, a second analysis of these alternative fiber crops was conducted, and the results ranked hemp first, flax second, and organic cotton third with a greater variance between the Net Sustainability Scores. The results of this secondary evaluation, of which the robustness was tested under a series of sensitivity analyses, were interesting because, while each alternative fiber crop performed better on some criteria over others, hemp emerged as the most sustainable crop overall. This result was surprising because hemp has been very tightly regulated by the United States government for nearly eighty years as a result of its conflation with psychotropic marijuana, which is also a variety of *Cannabis sativa*.

Consequently, an examination of the barriers to commercial-scale hemp production was initiated, and recommendations to overcoming the relevant barriers was outlined in the sections above. If relevant stakeholders, like policymakers, farm service providers, agronomists, lenders,

processors, brands, and consumers, focus on overcoming some of these barriers discussed, the cultivation of hemp is more likely to be expanded in the United States.

Even though hemp was deemed the most sustainable fiber crop for production in the southeastern United States in this PROMETHEE evaluation and a series of sensitivity analyses confirmed this, there were a number of limitations to the efficacy of these results. First, this evaluation relied on secondary production data and the availability of this data determined the crops and criteria that could be included in the framework. If data was not available for particular crops or criteria, it was not included in the evaluation. Secondly, the data was derived from production sources within the southeastern United States, as all four natural fiber crops are adapted to production there; however, this narrow geographic scope limits the applicability of the evaluation for crop production in other regions of the United States.

While steps were taken to overcome the limitations of this analysis, as discussed in detail throughout this paper, the results could be influenced by some of these limitations. For instance, if other fiber crops, like bamboo or kenaf, could be included in the analysis, or alternative criteria like Pesticide Application Rate, would hemp still remain top-ranked as the most sustainable crop? Therefore, this evaluation, and others PROMETHEE analyses like it, serve as general frameworks that can be continuously modified and improved as more information is available or as production objectives change to support this research's Natural Fiber Crop Sustainability Index, or generate an alternative index of other crops. Future PROMETHEE analyses of natural fiber crops would benefit from referring to the research presented in this paper as a foundational process for building an evaluation framework to measure the sustainability of natural fiber crop cultivation.

Hopefully this research and its results may be useful to farmers in the southeastern United States who are interested in cultivating natural fiber crops. While future analyses may result in alternative crop sustainability scores and indices, this study illuminated the benefits of producing and using natural fibers instead of synthetic fibers, and the multitude of social, economic, and environmental benefits these crops, and fibers, provide. Ultimately, it is hoped that the global fiber supply chain—of processors, manufacturers, brands, consumers, and farmers—are inspired by this study, and subsequent future research. It is critical that support for the cultivation of a diversity of natural fiber crops across the globe in sustainable agricultural systems, appropriate to regional conditions, grows to ensure that production of, and the natural fibers produced, uphold

environmentally-soundness, resource conservation, and social benefit—the foundation of sustainable agriculture (Ikerd, 1993).

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## Appendix A

## Crop Profiles for Conventional Cotton, Flax, Hemp, and Organic Cotton

**COTTON (CONVENTIONAL)***Gossypium barbadense; Gossypium hirsutum*

Figure 8. Cotton plant drawing. Reprinted from *Wikimedia Commons*, 1875. Retrieved from [https://commons.wikimedia.org/wiki/File:Cotton\\_Plant\\_Drawing.jpg](https://commons.wikimedia.org/wiki/File:Cotton_Plant_Drawing.jpg)

**PRODUCTION HISTORY**

Evidence of cotton production was recorded as early as 5000 B.C (Fisher, 2006). The first cotton crops were planted in the United States in 1621 (Smith & Cothren, 1999). Over the following century production intensified in the southeastern United States, especially after the invention of the cotton gin in 1793, which led to major issues of racial conflict between plantation owners and slaves (Smith & Cothren, 1999).

**CURRENT PRODUCTION STATUS**

Today, cotton is still cultivated intensely in monocrop agricultural systems in the southern and western regions of the United States (United States Congress, Office of Technology Assessment, 1987). The United States is the world's third largest cotton producer, planting 14 million acres (with an expected harvest of 19.7 million bales) in 2018, and is the top cotton exporter (Meyer, 2018). Other top producers include China, Brazil, India, Pakistan, and Uzbekistan ().

**CROP CHARACTERISTICS**

Compared to other natural fiber crops, cotton is water-intensive and prone to pests. The intensive monocropping of cotton in the United States and around the world on 2.3% of global arable land (33 million hectares), requires 14% percent of all agricultural insecticides, and accounts for one percent of all global greenhouse gas emissions (Kelley, 2017).

**CROP PRODUCTS**

Cotton produces high-quality seed fiber that is spun into soft, breathable, absorbent and strong fabric for garments and textiles (Food and Agriculture Organization of the United Nations, 2009). Cotton seeds can also be harvested and used in cotton seed oil for human and animal consumption.

## Appendix A

## Crop Profiles for Conventional Cotton, Flax, Hemp, and Organic Cotton

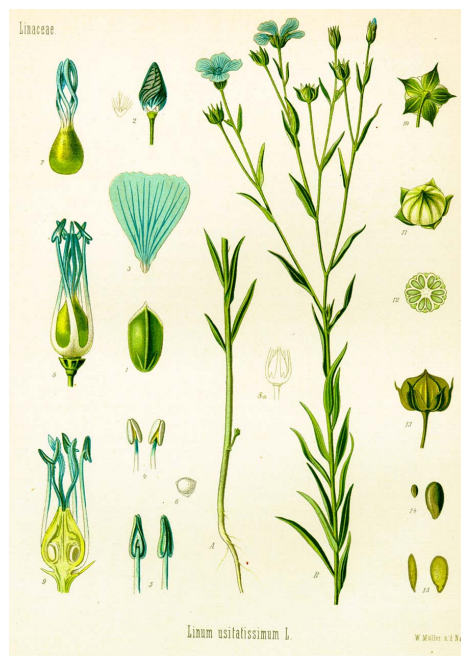
**FLAX***Linum usitatissimum*

Figure 9. Flax. Reprinted from *Wikimedia Commons*, by Franz Eugen Kohler, 1883. Retrieved from [https://commons.wikimedia.org/wiki/File:Flax\\_large.jpg](https://commons.wikimedia.org/wiki/File:Flax_large.jpg)

**PRODUCTION HISTORY**

Flax was one of the earliest domesticated crops. Evidence of flax production for its natural fiber to make linen dates back to 8000 BC. Flax has been grown in the United States since colonial times, and the crop was cultivated in nearly every state east of the Mississippi (Jefferson Institution, n.d.). Commercial production expanded from 1753 until 1793 when cotton production intensified as a result of the invention of the cotton gin (Hamlin, n.d.). The advent of synthetic fibers in 1950 caused flax production in the United States to decline to nearly zero (Jefferson Institution, n.d.)

**CURRENT PRODUCTION**

Currently, production of fiber flax in the United States is negligible, but the crop is being researched in US states in the South Atlantic region (Foulk, Akin, Dodd, & Frederick, 2004). However, seed flax is grown in north central states like North Dakota. (Hamlin, n.d.) Imports of flax fiber and products come from China and eastern Europe.

**CROP CHARACTERISTICS**

Flax is a cold-tolerant, annual plant with a deep root system. The plant requires moderate temperatures and sufficient rainfall (Hamlin, n.d.). Further, flax's hardiness in cooler climates provides an economic opportunity for farmers in region's unsuitable for food production and reduces competition for fertile land (Ellen MacArthur Foundation, 2017).

**CROP PRODUCTS**

As a bast crop, flax's fiber structure is more crystalline than cotton, creating a stronger, crisper, and stiffer linen fabric (Woven in KY; MacArthur). In addition to producing flax fiber for linen, the fiber is used in paper, bioplastics and composites, and biomass for energy production. Flax's seeds and oil are nutrient dense and used in cosmetics, foods, and supplements (Food and Agriculture Organization of the United Nations, 2009). Linseed oil is also used as a drying agent for paints, varnishes, and inks (Hamlin, n.d.; Jefferson Institute, n.d.).



## Crop Profiles for Conventional Cotton, Flax, Hemp, and Organic Cotton

**HEMP***Cannabis sativa L.*

Figure 10. Hemp – fibre plants. Reprinted from *Wikimedia Commons*, 1883. Retrieved from [https://commons.wikimedia.org/wiki/File:NIE\\_1905\\_Hemp\\_-\\_Fibre\\_Plants.jpg](https://commons.wikimedia.org/wiki/File:NIE_1905_Hemp_-_Fibre_Plants.jpg)

**PRODUCTION HISTORY**

According to Cherney & Small (2016), hemp (*Cannabis sativa L.*) was one of the earliest domesticated crops, cultivated for millennia beginning as a crop follower in pre-agricultural, nomadic societies across Eurasia. Hemp was first brought to North America in 1606, where it was grown for fiber across the continent for hundreds of years, thriving in Kentucky from 1840 to 1912, despite the reduction in hemp's use after the invention of the cotton gin in the late eighteenth century (Hamlin, n.d.). Prevention and Control Act in 1970, placed hemp cultivation under control of the United States government because of its relation to marijuana, a variety of psychotropic cannabis (Cherney & Small, 2016).

**CURRENT PRODUCTION**

As in the United States, a number of countries banned production of hemp throughout the twentieth century because of the psychoactive chemical that naturally occurs in *Cannabis sativa* (Ellen MacArthur Foundation, 2017). Though, it is documented that production of hemp for fiber contains very low amounts of the chemical tetrahydrocannabinol (Ellen MacArthur Foundation, 2017). As widespread prohibition of hemp cultivation around the globe has been overturned, the production of hemp for fiber has increased by 80%, with more than half of the 90,000 tons produced annually cultivated in China, and the remainder grown in parts of Europe, Chile, and South Korea (Food and Agriculture Organization of the United Nations, 2009).

**CROP CHARACTERISTICS**

Hemp is a naturally weedy species, and its natural oils do not appeal to pests; therefore, it does not require herbicides or insecticides (Cherney & Small, 2016). At maturity, the stalks can reach a height of 4 meters, capturing large quantities of carbon (Food and Agriculture Organization of the United Nations, 2009). Further, hemp's deep roots, which extend 2.5 meters help to prevent erosion, and fix nutrients into the soil. Bast fibers, like flax and hemp, are adaptable for cultivation on land unsuitable for food production (Ellen MacArthur, 2017) Finally, the fiber from the hemp plant is removed through a decomposition process called retting, wherein the harvested stalks are left to decompose in the field for several weeks until the cellulosic fiber can be more easily removed from the plant's core. Thusly, by leaving some plant matter in the field post-harvest and retting, organic matter can be returned to the soil to increase soil health.

**CROP PRODUCTS**

According to Cherney & Small (200?), there are as many as 50,000 uses claimed for hemp products. Hemp fibers conduct heat, dye well, resist mildew, block ultraviolet light, and have natural antibacterial properties making it as useful garment and textile fabric on its own or as a blend with other fabrics (Food and Agriculture Organization of the United Nations, 2009). In addition, bast fibers, which are four times stronger than cotton and twice as resistant to abrasion, are preferred for creating composite materials and bioplastics for automotive and construction applications (Cherney & Small, 2016; Allwood, 2006). Hemp fibers are also used in paper, animal bedding, biofuels and ethanol, as a natural food product, and in cosmetics and pharmaceuticals.

## Appendix A

## Crop Profiles for Conventional Cotton, Flax, Hemp, and Organic Cotton

**COTTON (ORGANIC)***Gossypium barbadense; Gossypium hirsutum*

Figure 8. Cotton plant drawing. Reprinted from *Wikimedia Commons*, 1875. Retrieved from [https://commons.wikimedia.org/wiki/File:Cotton\\_Plant\\_Drawing.jpg](https://commons.wikimedia.org/wiki/File:Cotton_Plant_Drawing.jpg)

**PRODUCTION HISTORY**

The establishment of the National Organic Program in the United States in 1990 provided a framework by which to certify crops produced “using cultural, biological, and mechanical practices that support the cycling of on-farm resources, promote ecological balance, and conserve biodiversity in accordance with the USDA organic regulations...synthetic fertilizers, sewage sludge, irradiation, and genetic engineering may not be used (United States Department of Agriculture, Agricultural Marketing Service. (n.d.).

Beginning in the 1990s, farmers producing organic cotton in United States were eligible to be certified organic.

**CURRENT PRODUCTION STATUS**

Of the roughly 20 million bales of cotton planted in the United States in 2017, only about 0.1% is certified organic (20,896 bales) and just 0.003% (811 bales) is in transition to organic production; yet, this share is up 1% and growing from 2017, as farmers seek to take advantage of premium prices and growing demand for organic cotton (United States Department of Agriculture, Agricultural Marketing Service, 2018d). Most American organic cotton is produced in west Texas, with minimal production in California and North Carolina. The vast majority of organic cotton is produced internationally in 18 countries.

**CROP CHARACTERISTICS**

Because certified organic cotton production does not permit the use of synthetic, petroleum-based agrochemicals, production enhances biodiversity and reduces pollution of soil and water ways as a result of runoff or drift.

A life cycle assessment (LCA) of organic cotton by Textile Exchange determined production of cotton in organic, instead of conventional systems, led to a 46% reduction in global warming contribution due to reduced agricultural inputs like chemicals, mechanized harvesting, and irrigation; a 70% reduction in acidification of land and water; a 26% decrease in over fertilization; a 91% reduction in water consumption due to rainfed irrigation; a 62% decrease in energy use (Textile Exchange, 2017).

**CROP PRODUCTS**

Organic cotton produces the same high-quality fiber and seed oil; however, due to its organic certification, it can be marketed and sold for nearly 50% more than conventional cotton (Allwood et al, 2006).

Appendix B

Sustainability Criteria Selected for PROMETHEE Fiber Crop Evaluation

Table 7.

Crop Data Collected for Each Criterion Selected for PROMETHEE Evaluation

Unit of Measurement	SOCIAL				ECONOMIC				ENVIRONMENTAL					
	OPERATOR & CUSTOM LABOR	NOTE & CITATION	FIBER COMMUNITY	NOTE & CITATION	FIBER INCOME	NOTE & CITATION	FIBER YIELD	NOTE & CITATION	NITROGEN FERTILIZER REQUIREMENT	NOTE & CITATION	WATER REQUIREMENT	NOTE & CITATION	BIODIVERSITY FRIENDLINESS SCORE	NOTE & CITATION
<i>Maximized or Minimized in PROMETHEE Evaluation</i>	<i>Minimized</i>		<i>Maximized</i>		<i>Maximized</i>		<i>Maximized</i>		<i>Minimized</i>		<i>Minimized</i>		<i>Maximized</i>	
<b>FLAX</b>	<b>\$34.97/acre</b> (\$43.25 in 2016 CAD = \$29.55 [custom work] + \$13.70 [operator labor])	Canadian proxy data converted to 2018 \$USD; Ontario Ministry of Agriculture, Food and Rural Affairs, 2016	<b>3,350 acres</b> (NC [35 acres], SC [300 acres - CRAILAR; 3,000 acres])	North Carolina Department of Agriculture & Consumer Services, 2013; Securities and Exchange Commission	<b>\$0.14/pound</b> (\$250/ton [\$0.125/pound] in 2013)	Data converted to 2018 \$USD; North Carolina Department of Agriculture & Consumer Services, 2013	<b>5,220 pounds/acre</b> (3.48 tons/acre)	North Carolina Department of Agriculture & Consumer Services, 2013	<b>60 pounds/acre</b>	North Carolina Department of Agriculture & Consumer Services, 2013	<b>27.56 inches/season</b> (700 millimeters)	Faulk, Akin, Dodd & McAllister, 2002	<b>-4</b>	Montford & Small (1999)
<b>HEMP</b>	<b>\$87.05/acre</b> (\$56.00/acre in 1997 dollars)	Data converted to 2018 \$USD; United States Department of Agriculture, Economic Research Service, 2000	<b>4,436 acres</b> (KY [3,271], NC [965], TN [200])	Vote Hemp, 2017	<b>\$0.34/pound</b>	Kansas Department of Agriculture, 2018	<b>2,556 pounds/acre</b>	Kansas Department of Agriculture, 2018	<b>115 pounds/acre</b> (averaged total of 100-130 pounds/acre)	Purdue University, n.d.	<b>13.50 inches/season</b> (averaged total 12-15 inches)	Cornell University, 2017	<b>2</b>	Montford & Small (1999)
<b>ORGANIC COTTON</b>	<b>\$213.18/acre</b> (\$128.47/acre in 1995 dollars)	California proxy data converted to 2018 \$USD; University of California Cooperative Extension, 1995	<b>50 acres</b> (NC)	Rodale Institute, 2013; Textile Exchange, 2012	<b>\$1.68/pound</b> (\$1.675/pound = averaged price of \$1.05-\$2.30/pound)	United States Department of Agriculture, Agriculture Marketing Service, 2018c	<b>502 pounds/acre</b>	Organic Trade Association, n.d.	<b>0 pounds/acre</b>	United States Department of Agriculture, Office of Communications, 2015	<b>24.95 inches/season</b> Average daily crop evapotranspiration (inch) = (0.09**25 days)+(0.22**35 days)+(0.30**50 days)	Cotton Incorporated, n.d.	<b>N/A</b>	Montford & Small (1999) did not calculate organic cotton's Biodiversity Friendliness Score.
<b>CONVENTIONAL COTTON</b>	<b>\$51.96/acre</b>	National Cotton Council of America, 2018	<b>950,000 acres</b> (NC, SC, TN)	United States Department of Agriculture, 2018a	<b>\$0.71/pound</b> (\$1.675/pound = averaged price of \$1.05-\$2.30/pound)	United States Department of Agriculture, Agriculture Marketing Service, 2018b	<b>794 pounds/acre</b>	National Cotton Council of America, 2018	<b>88 pounds/acre</b> (averaged total of 30-80 pounds/acre)	United States Department of Agriculture, Office of Communications, 2015	<b>24.95 inches/season</b> Average daily crop evapotranspiration (inch) = (0.09**25 days)+(0.22**35 days)+(0.30**50 days)	Cotton Incorporated, n.d.	<b>-7</b>	Montford & Small (1999) did not calculate organic cotton's Biodiversity Friendliness Score.

Appendix C

Sustainability criteria selected for evaluation

Table 8.

*Sustainability Criteria Selected for PROMETHEE Evaluation*

Sustainability Dimension	Criterion from Literature Review	Literature Citation	Indicator Name Used in this Research	Unit of Measurement Used in this Research	Maximize/Minimize Criterion in PROMETHEE Evaluation	Sustainability Rationale
Social Criteria	Education Programs/Resources	Miranda, 2001	Fiber Community	Acres produced in southeastern states (KY, NC, SC, TN)	Maximize	The Fiber Community criterion represents the strength of the network of fiber crop producers, measured in total acres produced. A larger production community (higher acreage total) provides a social benefit to farmers reestablishing fiber production. More acreage in production for each crop indicates that more regional-specific information and resources are being established that can be shared with other producers, which is inspired by the farmer-to-farmer cooperation and collaboration of the Fibershed movement. A larger community allows for nascent crop production systems to be better-supported and for increased knowledge-sharing between farmers. This criterion simplifies the education/resources, cooperation, and sociability indicators from the literature, of which determine a farmer’s social well-being. Fiber Community should be <b>maximized</b> in the model as a positive criterion for sustainability, despite its traditional indication that more acreage in production leads to increased competition and consolidation.
	Cooperation with other farmers	Kask & Lengnick, 2009				
	Sociability	Miranda, 2001				
	Labour	Kylili, Christofourou, Fokaidis, & Polycarpou, 2016	Operator/Unpaid Labor	\$USD/acre	Minimize	The Operator/Unpaid Labor criterion signifies the cost of the farm operator to produce fiber crops. Higher labor costs divert farmer income to production, reducing the overall amount of money, and time, the operator can spend elsewhere. Operator labor costs were frequently cited as a social criterion that should be <b>minimized</b> in the model because they impact the farmer’s overall social well-being.
	Ratio Family/Other Farm Labor	Kask & Lengnick, 2009				
	Labour Productivity	Field to Market: The Alliance for Sustainable Agriculture, 2016				
Economic Criteria	Gross Agricultural Value	Dantsis, Douma, Giourga, Loumou,	Fiber Income	Income per unit of fiber produced	Maximize	The Fiber Income criterion represents the current revenue per unit of fiber produced for specific

		& Polychronaki, 2009		(\$/pound of fiber)		crops. Fiber Income should be <b>maximized</b> in the model as a positive criterion for economic sustainability as it promotes production of a crop to provide the highest financial return for the farmer. The Fiber Yield criterion indicates the total fiber produced per acre for the fiber crop. This criterion should be <b>maximized</b> in the model as the crop that can produce the most fiber per acre would guarantee greater economic return for the farmer.
	Crop Yield Income	Hasanshahi, Iravani, Ameri, & Kalantari, 2015				
	Profitability	Field to Market: The Alliance for Sustainable Agriculture, 2016				
	Biomass Production Yield	Cobuloglu & Buyuktahtakin, 2015	Fiber Yield	Total fiber yielded per acre (pounds of fiber /acre)		
Environmental Criteria	Water consumption	Dantsis, Douma, Giourga, Loumou, & Polychronaki, 2009	Water Requirement	Crop's water requirement (inches water/growing season)	Minimize	The Water Requirement criterion indicates the water needs of each fiber crop measured as inches of water/season. This criterion should be <b>minimized</b> in the model as crops that require a significant amount of water may rely on expensive and energy-intensive irrigation systems to achieve desired yield results, especially in water stressed regions, which puts pressure on local water systems. Crops with higher water requirements indicate poor sustainability performance.
	Irrigation Demand	Kylili, Christofourou, Fokaides, & Polycarpou, 2016; Field to Market: The Alliance for Sustainable Agriculture, 2016				
	Water Efficiency	Kask & Lengnick, 2009				
	Water Requirement	Cobuloglu & Buyuktahtakin, 2015				
	Water Application	Hasanshahi, Iravani, Ameri, & Kalantari, 2015	Synthetic Nitrogen Fertilizer Requirement	Crop's synthetic nitrogen fertilizer requirement (pounds of Nitrogen/acre)	Minimize	The Nitrogen Requirement criterion represents the nitrogen needs of each fiber crop measured as the amount added to the soil in the form of chemical and/or synthetic fertilizers. This indicator should be <b>minimized</b> in the model as crops that require a significant amount of nitrogen amendment can cause excess nitrogen runoff into air- and waterways and soil, which leads to reduced ecosystem function, and impacts of air and water quality (Ham, 2016). It can also cause eutrophication, acid rain, and contribute to the greenhouse effect, as well as health impacts like
	Use of Fertilizers	Dantsis, Douma, Giourga, Loumou, & Polychronaki, 2009				
	Fertilizer Demand	Kylili, Christofourou, Fokaides, & Polycarpou, 2016				
	Fertilizer Application	Hasanshahi, Iravani, Ameri, & Kalantari, 2015				
	Use of Fertilizers	Miranda, 2001				

						methemoglobinemia (blue baby syndrome), cancers, diabetes, adverse thyroid and reproductive conditions (Ward, 2008).
	Biodiversity Friendliness Score	Montford & Small, 1999	Biodiversity Friendliness Score	Y = positive, N = negative, N/A = no data available	Maximize	A paper by Montford & Small (1999) established a “Biodiversity Friendliness Score” for a number of crops, including cotton, flax, and hemp, using 26 criteria that were assigned values of -1 (undesirable impact), 0 (average impact), or 1 (most desirable impact) depending on their ecological friendliness. The total score for each crop was calculated as a positive or negative value. This criterion was included to round out the environmental criteria used for evaluation as no data could be found for other environmental criteria. It should be <b>maximized</b> in the model, as a higher score indicates a more environmentally-sound crop.

## Appendix D

## Computational Theory of PROMETHEE

PROMETHEE is an outranking MCDA method that compares the performance each alternative against a set of criteria in order to identify the optimal option or decision, ranks alternatives from best to worst, classifies alternatives, visualizes problems. PROMETHEE's computational theory is defined as:

$$\max \{f_1(a), f_2(a), \dots, f_j(a), \dots, f_k(a) | a \in A\}$$

where  $A$  is a finite set of  $n$  actions and  $f_1$  to  $f_k$  are  $k$  criteria.  $f_j(a)$  is the evaluation of action  $a$  on criterion  $f_j$ .

Figure 11. PROMETHEE computational theory (I). Reprinted from *PROMETHEE-GAIA*, 2013.

Retrieved from <http://www.promethee-gaia.net/assets/vpmanual.pdf>

PROMETHEE requires that the evaluator set preferences for each criterion being applied in the model by maximizing or minimizing each criterion under evaluation, as well as define a preference function and indifference and preference thresholds that determine the extent to which deviations are considered negligible (indifference threshold) and the smallest deviation considered sufficient to generate a full preference (preference threshold) for each criterion (Visual PROMETHEE, 2013).

This preference function determines the deviation so that the software can effectively compile an index that accurately represents the evaluator's objectives. Small deviations imply weak or no preference for a particular action, which larger deviations indicate stronger preference for a particular action (Visual PROMETHEE, 2013). Deviations are based the preference function selected by the evaluator and normalized to a range between 0-1 (Visual PROMETHEE, 2013). PROMETHEE software includes six types of preference functions to be selected by the evaluator, but this model uses only Type V, the Linear preference function, (with Type III, V-shape, as a special case), which is the best choice for most quantitative criteria (Visual PROMETHEE, 2013).

After setting the preference function and performing the analysis, PROMETHEE computes preference flows to consolidate the results of the pairwise comparisons of the actions and to rank all the actions from the best to the worst one. Three different preference flows are computed by Visual PROMETHEE (2013).

Phi+ positive flow measures how much an alternative  $a$  is preferred to the other  $n-1$  ones



$$\phi^+(a) = \frac{1}{n-1} \sum_{b \neq a} \pi(a, b)$$

Figure 12. PROMETHEE computational theory (II). Reprinted from *PROMETHEE-GAIA*, 2013. Retrieved from <http://www.promethee-gaia.net/assets/vpmanual.pdf>

**Phi- negative flow** measures how much the other  $n-1$  alternatives are preferred to alternative  $a$ .

$$\phi^-(a) = \frac{1}{n-1} \sum_{b \neq a} \pi(b, a)$$

Figure 13. PROMETHEE computational theory (III). Reprinted from *PROMETHEE-GAIA*, 2013. Retrieved from <http://www.promethee-gaia.net/assets/vpmanual.pdf>

Phi net flow is the balance of the positive and negative preference flows and aggregates a single score.

$$\phi(a) = \phi^+(a) - \phi^-(a)$$

Figure 14. PROMETHEE computational theory (IV). Reprinted from *PROMETHEE-GAIA*, 2013. Retrieved from <http://www.promethee-gaia.net/assets/vpmanual.pdf>

The Phi net flow scores are used to construct the PROMETHEE preference index. The alternative with a score closest to 1, indicating a strong preference for that alternative based on the comparisons, ranks first, followed by the others in descending order according to the Phi scores. Those alternatives with scores closer to zero indicate weak overall performance of the alternative.

$$\pi(a, b) = \sum_{j=1}^k w_j \times P_j(a, b)$$

$w_j > 0$  is the normalized weight allocated to criterion  $f_j$  (the more important  $f_j$  the larger  $w_j$ ),  
 $P_j(a, b)$  is the value of the preference function for criterion  $f_j$  when action  $a$  is compared to action  $b$ .

Figure 15. PROMETHEE computational theory (V). Reprinted from *PROMETHEE-GAIA*, 2013. Retrieved from <http://www.promethee-gaia.net/assets/vpmanual.pdf>



Appendix E  
Four-Crop Visual PROMETHEE Evaluation Matrix

Scenario1	Labor Requir...	Community	Income	Yield	Nitrogen Fer...	Water Requi...	Biodiversity ...
Unit	\$USD/acre/sea	crop acreage in	\$USD/pound	pounds	pounds	inches	aggregate
Cluster/Group	◆	◆	●	●	■	■	■
<b>Preferences</b>							
Min/Max	min	max	max	max	min	min	max
Weight	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	\$ 0.00	0.00	\$ 0.00	0.00	0.00	0.00	0.00
- P: Preference	\$ 178.21	940950.00	\$ 1.54	4718.00	115.00	14.06	9.00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a
<b>Statistics</b>							
Minimum	\$ 34.97	50.00	\$ 0.14	502.00	0.00	13.50	-7.00
Maximum	\$ 213.18	941000.00	\$ 1.68	5220.00	115.00	27.56	2.00
Average	\$ 96.79	237209.00	\$ 0.72	2268.00	57.50	21.42	-3.00
Standard Dev.	\$ 69.77	406337.13	\$ 0.59	1876.74	40.70	5.38	3.74
<b>Evaluations</b>							
<input checked="" type="checkbox"/> Flax	\$ 34.97	3350.00	\$ 0.14	5220.00	60.00	27.56	-4.00
<input checked="" type="checkbox"/> Hemp	\$ 87.05	4436.00	\$ 0.34	2556.00	115.00	13.50	2.00
<input checked="" type="checkbox"/> Organic Cotton	\$ 213.18	50.00	\$ 1.68	502.00	0.00	24.95	n/a
<input checked="" type="checkbox"/> Conventional Co...	\$ 51.96	941000.00	\$ 0.71	794.00	55.00	19.68	-7.00

Visual PROMETHEE Academic - 3 CROP UPDATE.vpg (saved)

File Edit Model Control PROMETHEE-GAIA GDSS GIS Custom Assistants Snapshots Options Help

Actions: 4 (4 active) Criteria: 8 (7 active) Scenarios: 2 (2 active) Locale: USA [\$/.] Saved

Figure 16. Four-crop Visual PROMETHEE evaluation matrix.

Appendix F  
 Three-Crop Visual PROMETHEE Evaluation Matrix

Scenario1	Labor Requir...	Community	Income	Yield	Nitrogen Fer...	Water Requi...	Biodiversity ...
Unit	\$USD/acre/sea	crop acreage in	\$USD/pound	pounds	pounds	inches	aggregate
Cluster/Group	◆	◆	●	●	■	■	■
<b>Preferences</b>							
Min/Max	min	max	max	max	min	min	max
Weight	1.00	1.00	1.00	1.00	1.00	1.00	1.00
Preference Fn.	Linear	Linear	Linear	Linear	Linear	Linear	Linear
Thresholds	absolute	absolute	absolute	absolute	absolute	absolute	absolute
- Q: Indifference	\$ 0.00	0.00	\$ 0.00	0.00	0.00	0.00	0.00
- P: Preference	\$ 178.21	4386.00	\$ 1.54	4718.00	115.00	14.06	6.00
- S: Gaussian	n/a	n/a	n/a	n/a	n/a	n/a	n/a
<b>Statistics</b>							
Minimum	\$ 34.97	50.00	\$ 0.14	502.00	0.00	13.50	-4.00
Maximum	\$ 213.18	4436.00	\$ 1.68	5220.00	115.00	27.56	2.00
Average	\$ 111.73	2612.00	\$ 0.72	2759.33	58.33	22.00	-1.00
Standard Dev.	\$ 74.82	1865.07	\$ 0.68	1931.47	46.96	6.11	3.00
<b>Evaluations</b>							
<input checked="" type="checkbox"/> Flax	\$ 34.97	3350.00	\$ 0.14	5220.00	60.00	27.56	-4.00
<input checked="" type="checkbox"/> Hemp	\$ 87.05	4436.00	\$ 0.34	2556.00	115.00	13.50	2.00
<input checked="" type="checkbox"/> Organic Cotton	\$ 213.18	50.00	\$ 1.68	502.00	0.00	24.95	n/a

Figure 17. Three-crop Visual PROMETHEE evaluation matrix.

Appendix G

Visual PROMETHEE Output: Social Criteria Sensitivity Analysis

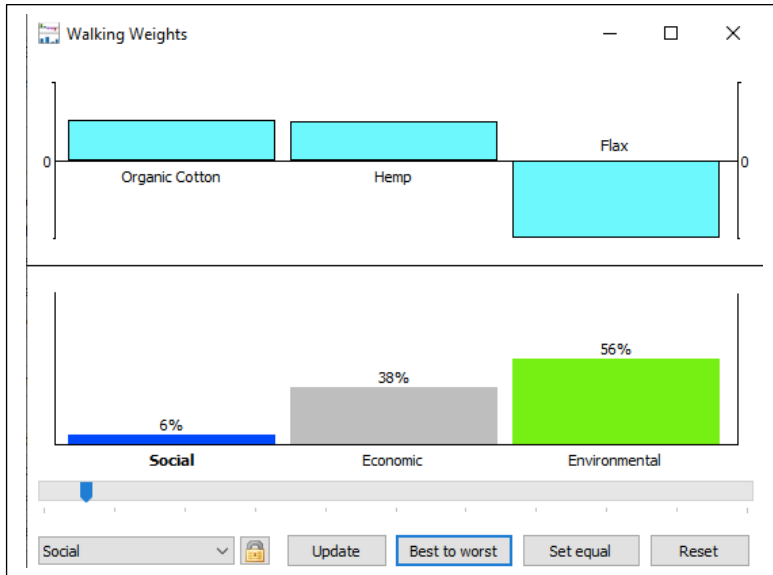


Figure 18. Social criteria sensitivity analysis I.

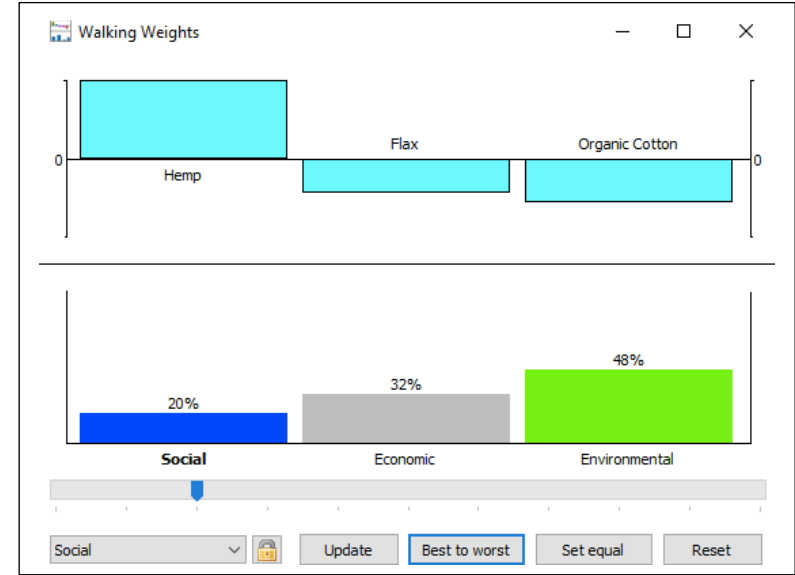


Figure 19. Social criteria sensitivity analysis II.

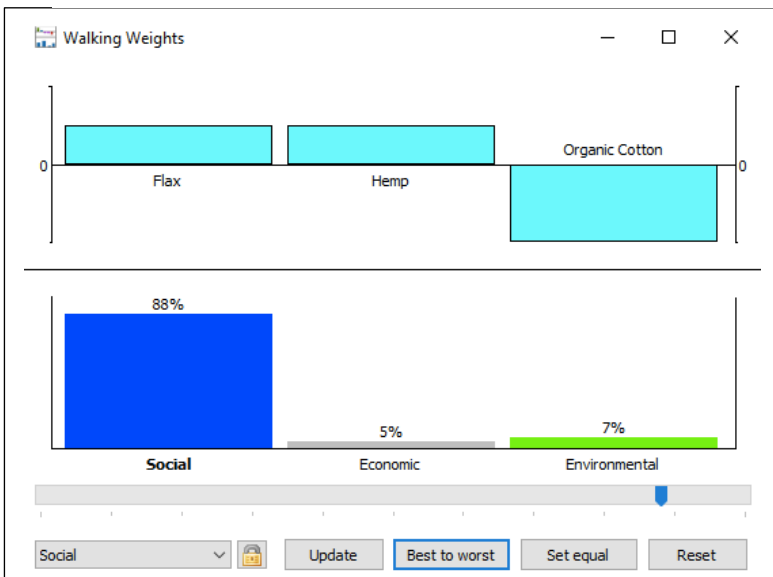


Figure 12. Social criteria sensitivity analysis III.

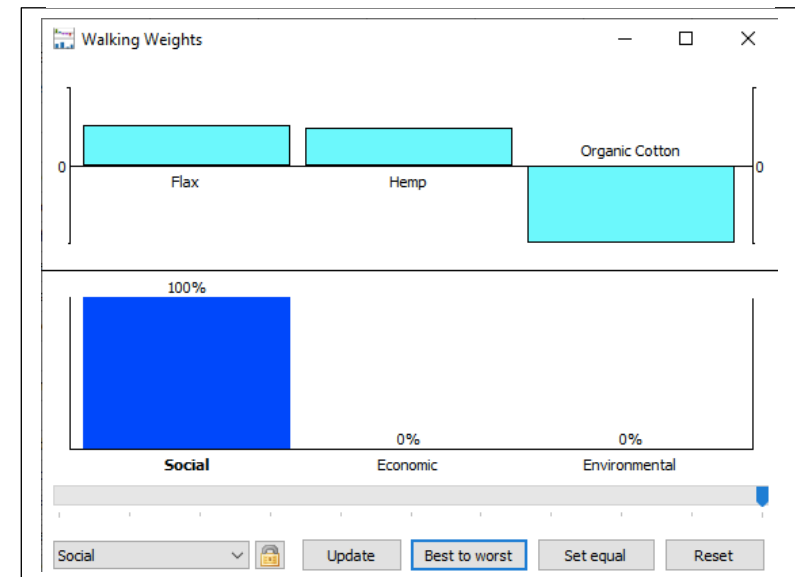


Figure 21. Social criteria sensitivity analysis IV.

Appendix H

Visual PROMETHEE Output: Environmental Criteria Sensitivity Analysis

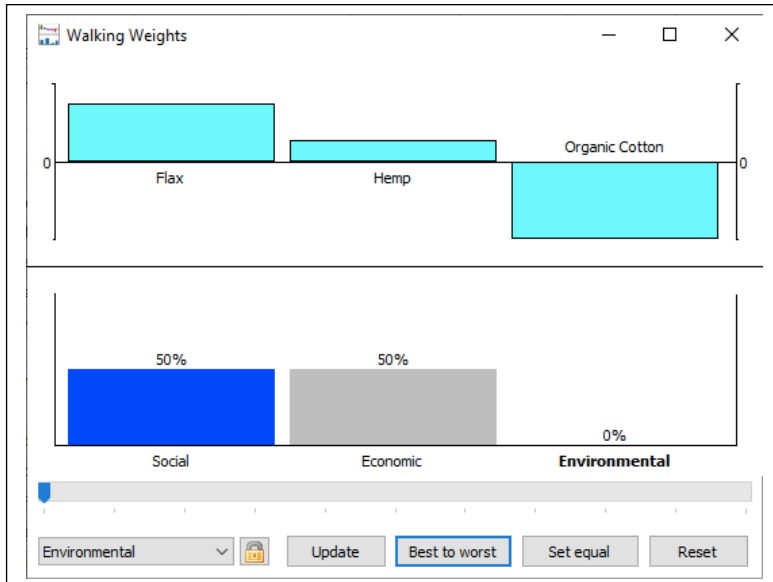


Figure 22. Environmental criteria sensitivity analysis I.

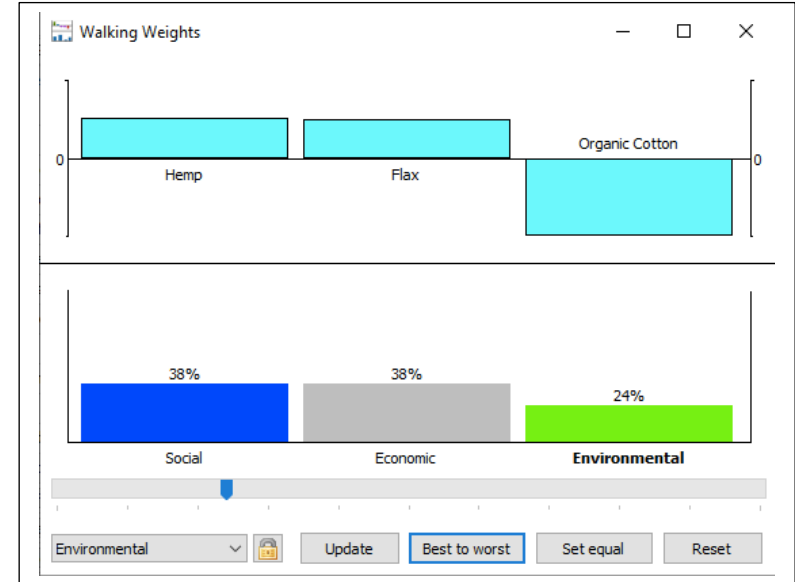


Figure 23. Environmental criteria sensitivity analysis II.

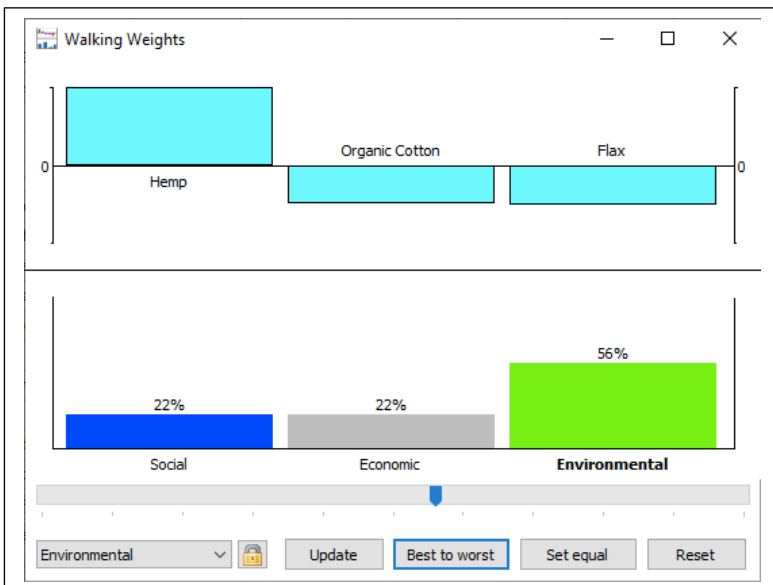


Figure 24. Environmental criteria sensitivity analysis III.

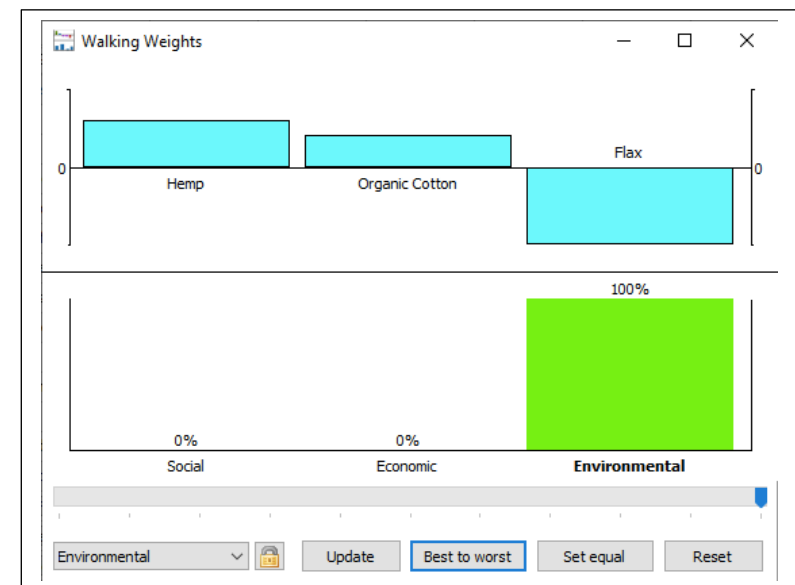


Figure 25. Environmental criteria sensitivity analysis IV.

Appendix I

Visual PROMETHEE Output: Economic Criteria Sensitivity Analysis

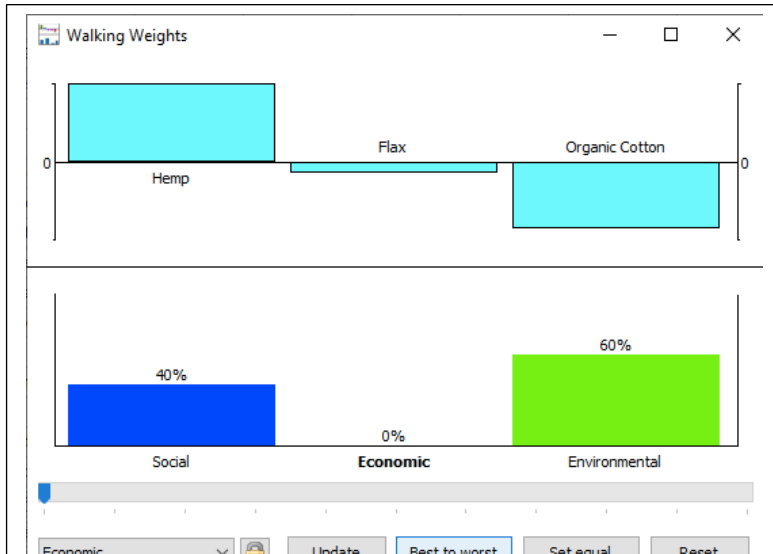


Figure 26. Economic criteria sensitivity analysis I.

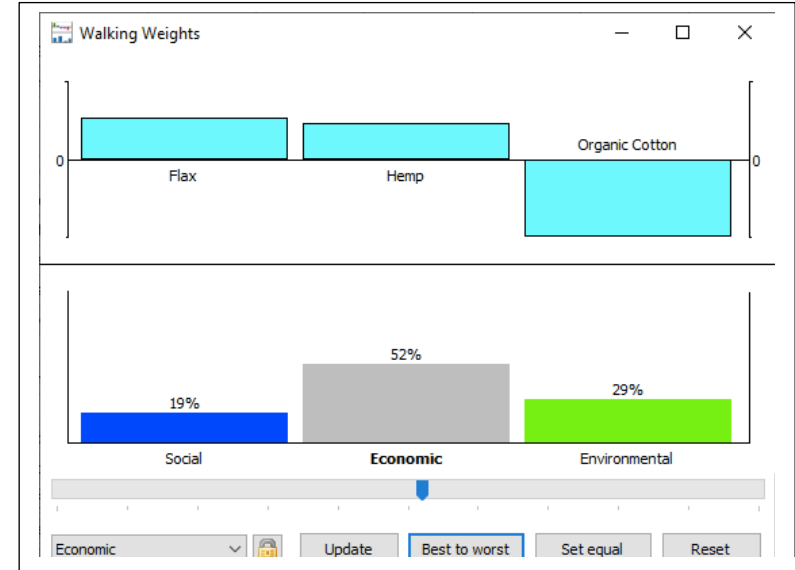


Figure 27. Economic criteria sensitivity analysis II.

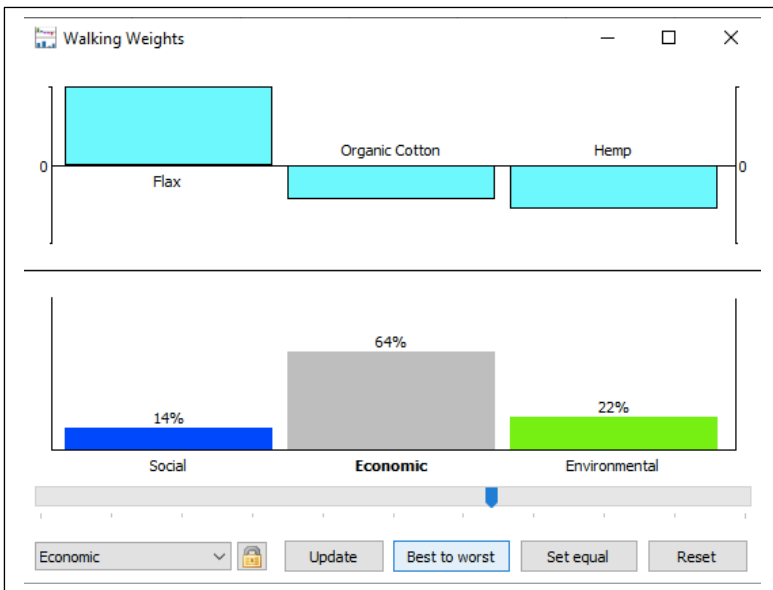


Figure 28. Economic criteria sensitivity analysis III.

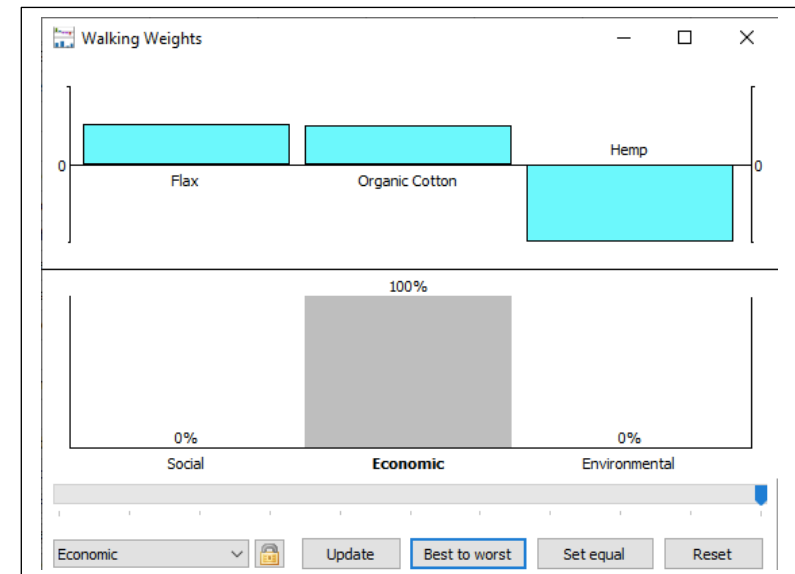


Figure 29. Economic criteria sensitivity analysis IV.

