BIO-BASED FIBER PRODUCTION IN THE EUROPEAN UNION

A spatial analysis of potential biomass production to substitute the European demand for synthetic fibers

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Abstract

The fashion industry is one of the most polluting industries globally, and it largely depends on fibers made from non-renewable resources. The EU wants to move away from these non-renewable resources by increasing the number of bio-based products produced in the EU. At the same time, the EU Bioeconomy aims to ensure food security and sustainable management of natural resources, goals that are also reflected in other recent strategies of the EU Green Deal. This paper studied whether the production of bio-based textile fibers to replace synthetic fibers is possible without harming food security and natural resources by using abandoned farmland across the EU. A substantial amount of the abandoned land was excluded from the analysis to accommodate the Biodiversity Strategy goals. The findings indicate that most abandoned land and the most potential for bio-based fiber production is found in Poland. This country is followed by Italy, Spain, Portugal, Lithuania, and Germany, and together these top 6 countries produce over 75% of the total measured potential. However, even in the best-case scenario, the total production potential is 39% of the total EU demand for synthetic fibers. This means that bio-based fibers can reduce dependence on non-renewable resources, but other measures are also needed.

Key words: EU Bioeconomy, EU Green Deal, Farm to Fork Strategy, Biodiversity Strategy, bio-based fibers, abandoned land

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Abbreviations

CAP	Common Agricultural Policy
CEE	Central and Eastern Europe
EC	European Commission
EEA	European Environment Agency
EFI	European Forest Institute
EU	European Union
FAOSTAT	Food and Agriculture Organization of the United Nations Statistical Database
JRC	Joint Research Centre
PLA	Polylactic acid

1. Introduction

The emergence of fast fashion has made the fashion industry one of the most polluting industries in the world. Over the years, the global demand for clothing has grown tremendously, and the fashion industry currently accounts for around 10% of global greenhouse gas emissions [1]. While in 1975, the global textile production per capita was 5.9 kg per year, this production had more than doubled by 2018 [2]. In Europe, this number is even higher, with estimates of the average consumption per person ranging up to 27 kg of textiles yearly [3]. Clothing, footwear, and household textiles combined, around 13 million tons of textiles are used in the European Union (EU) in a single year [4]. More than half of these textiles are used for clothing [5]. This share will only grow since the demand for clothing is expected to keep increasing because of a growing population and rising GDP per capita, especially in developing countries. Compared to 2017, the demand for fashion is projected to have increased by 63% by 2030 [6].

The dispersed production of clothing is a prime example of globalization. Currently, only 7% of fiber production takes place in the EU [7]. The EU and other developed regions mainly import textile products from lower-labor-cost countries. Moreover, since many production steps are outsourced to other countries, production is further fragmented [2]. Because of this fragmentation, there is a lack of transparency on the working conditions of people in the supply chain and an uneven distribution of associated environmental impacts [8], [9]. In the lower-labor-cost countries, clothing is often made under very questionable social circumstances [8], which was global news when the Rana Plaza building collapsed, taking the lives of thousands of garment workers in the fashion industry [10]. At the same time, the industry puts much pressure on the environment through water, land, and energy use [2]. Recently, the fashion industry started implementing more sustainable practices to mitigate these impacts and achieve the Sustainable Development Goals [1]. However, this implementation is not going fast enough to counterbalance the growing demand for clothing [11].

The textile market is dominated by synthetic textiles, which are made from fossil fuels [2]. The most used synthetic fiber is polyester, which has steadily risen to become the most used fiber on the market due to its outstanding performance and low costs. Currently, more than half of all clothing fibers used are polyester, and this share will only increase further because developing countries are increasingly adopting Western lifestyle trends [2]. Essentially all fibers have some environmental impact, but polyester and other synthetic fibers differ from other fibers in that they are not made from renewable resources and are not biodegradable [12], [13]. Even though these fibers are recyclable, closed-loop recycling is done with less than 1% disposed of fabrics [5], and polyester alone accounts for around 10% of the global plastic waste [4]. Since fossil fuels are running out and around 48 million tons of textile waste are discarded yearly, there is an increasing interest in fibers that are made from renewable resources and can degrade after disposal [5], [14]. Cotton, the second most widely used fiber, has both these properties, but the production uses excessive amounts of water and pesticides that harm the environment [2], [15], [16].

The impact of both polyester and cotton has prompted the search for new alternatives like bio-synthetics [17] and increased interest in (regenerated) plant fibers like hemp and lyocell [18]. In contrast to synthetic fibers, bio-based fibers can be biodegradable and are made from renewable resources. At the same time, they have the potential to be less environmentally damaging than cotton. This interest is reflected in the EU Bioeconomy since this strategy aims to increase the production of bio-based products [19]. By implementing this strategy, the EU wants to move away from fossil fuels as a resource and reduce our dependence on non-renewables. This goal is reflected again in the Circular Economy Action Plan of the recently proposed EU Green Deal, which also wants to increase the number of bio-based products produced in the EU [20].

1.1 Problem statement

With a fast-growing population and a rising demand for clothing per capita, the need to act becomes increasingly urgent. Replacing synthetic fibers with bio-based fibers is heralded by many as one of the paths to more sustainable fashion [2], [5], [18], and the EU seems determined to follow this direction. However, the market share of bio-based fibers other than cotton is currently minimal [15]. Therefore, to replace a substantial number of synthetic fibers, these bio-based fibers will have to be produced at a larger scale. But producing these bio-based fibers is not without challenges since the necessary biomass production is constrained by land, water, labor use, and the non-renewable resources that remain necessary for production [21].

While there is much research on the bio-based fibers' mechanical and economic properties, limited studies have focused on the practical implications. One way to avoid competition with food production is to produce biomass on abandoned farmland [22]. However, the recultivation of this abandoned land to produce bio-based fibers has not been studied yet. Moreover, some scientists and NGOs are campaigning to use this abandoned land to rewild Europe and increase biodiversity [23], suggesting that this land might also be suitable to achieve the goals of the EU Biodiversity Strategy.

1.2 Research question

This thesis aims to understand whether considerable production of bio-based textile fibers can be achieved while also avoiding trade-offs with EU goals concerning food production and biodiversity. It sets out to answer the following research question:

How much of the EU demand for synthetic fibers can be replaced by bio-based fibers without harming food production or biodiversity goals?

The corresponding sub-questions are as follows:

1. What are the goals of the EU Bioeconomy and how do they correspond with strategies of the EU Green Deal?
2. How is recently abandoned farmland distributed in the EU and what are the reasons for and possible consequences of recultivating or rewilding these areas?
3. Which bio-based fibers can be a sustainable alternative to synthetic fibers and how are these fibers produced?
4. How is the potential to produce bio-based fibers distributed in the EU?

2. Theoretical background and context

2.1 EU Bioeconomy and other EU strategies

Scaling up the production of crops for bio-based materials is not without challenges since this biomass is also used for food and feed. Nevertheless, the EU wants to promote bio-based materials, and in 2012 the European Commission (EC) adopted the "Innovating for Sustainable Growth: A Bioeconomy for Europe" strategy [19]. The concept of the bioeconomy is defined by the EC as "the production of renewable biological resources and their conversion into food, feed, bio-based products, and bioenergy." ([19], p.11). The goals of the bioeconomy are as follows:

1. Ensure food and nutrition security
2. Manage natural resources sustainably
3. Reduce dependence on non-renewable unsustainable resources
4. Limit and adapt to climate change
5. Strengthen European competitiveness and create jobs

The overarching goals of the corresponding "Bioeconomy Action Plan" are to strengthen and scale up the bio-based sector and unlock investments and markets, deploy local bioeconomies rapidly across the whole of Europe, and understand the ecological boundaries of the bioeconomy [19].

In 2019, the EU Green Deal was announced. This plan is supposed to transform the EU into a "fair and prosperous society, with a modern, resource-efficient and competitive economy where there are no net emissions of greenhouse gases in 2050 and where economic growth is decoupled from resource use" ([20], p. 2). There are many proposed strategies in the EU Green Deal, all focusing on particular areas, but according to the EC, all "mutually reinforcing" ([20], p.4). At the heart of all these strategies is the Farm to Fork Strategy and the Biodiversity Strategy, which aim to maintain a healthy balance between nature, food, and biodiversity [24]. While the EU does not seem particularly concerned about trade-offs between the various strategies, one can wonder how the increase in biomass production needed for a strong bioeconomy will align with goals from these other two strategies since they all rely directly on land use.

The Farm to Fork Strategy aims to ensure sustainable food production with a neutral or positive environmental impact, ensure food security, and preserve food affordability while maintaining a fair supply chain [25]. Various methods have been proposed in the literature to decrease the environmental impact of food production. Whether the solution for sustainable farming is to intensify food production (land sparing) or include environmentally friendly practices (land sharing) is the cause of an active debate within the scientific community [19], [23]. Whichever solution is better, there is no question about a need for farmland that will only keep growing because of a growing population. Therefore, if crops for bio-based fibers need to be produced in coherence with the Farm to Fork Strategy, one should look for other land sources. Not using the current cropland also means that the increase in biomass production does not directly alter food security and affordability, which is similar to the first goal of the EU Bioeconomy.

Another critical aspect of the EU Green Deal is the Biodiversity Strategy. This strategy aims to increase the amount of protected land in the EU from 18 to 30%, return 25000 kilometers of river to a free-flowing state, and plant three billion trees before 2030 [26]. As with the Farm to Fork Strategy, we should not take land from these areas if these goals are to be met. In practice, this means that no land from within the protected Natura 2000 regions and no land close to rivers should be used to grow crops. Moreover, to obtain the 30% target of protected lands in 2030, more land should be kept aside. According to Van der Zanden et al. [27], an excellent candidate to increase protected lands would be potential habitat regions for megafauna. Megafauna species are essential for biodiversity and healthy ecosystems, but these species have decreased in the EU because of increased agricultural expansion and fragmentation [23]. By considering the goals of the Biodiversity Strategy, the production of bio-based products is also in line with the EU Bioeconomy's own second goal of managing natural resources sustainably. Currently, however, bio-based textiles are not necessarily produced sustainably.

For example, cotton is a bio-based textile, but growing it requires a lot of water and pesticides, putting stress on the surrounding environment and damaging other ecosystem services [15]. This illustrates the importance of sustainable farming; not only which crop is produced, but how it is produced makes a difference.

Considering the last three goals of the EU Bioeconomy, findings from the literature review suggest that these goals are indeed likely to be met. Almost all synthetic textiles are made from fossil fuel, a non-renewable resource [18]. Moreover, fossil-based synthetic fibers are not biodegradable. Replacing these fibers with bio-based ones will accomplish the challenge of reducing dependence on non-renewable resources. It can also help mitigate some of the fashion industry's environmental impacts, as the crops for bio-based fibers can act as a carbon sink for atmospheric carbon [2]. Regarding the challenge of creating jobs and maintaining European competitiveness, current findings show that this can be accomplished. The EU Bioeconomy is already estimated to be worth over 2.2 trillion euros and provides work to over 22 million people [19]. If the crops for bio-based fibers are produced within the EU, this could create even more jobs and economic competitiveness. Especially since the EU currently imports 1.78 million tons of synthetics yearly from other regions, like China [4].

This thesis aims to understand whether it is possible to produce bio-based textiles in coherence with these other strategies by not harming food production or biodiversity. Various papers have turned to abandoned farmland as a solution for biomass production that does not harm food production. Abandoned land is land that is previously used for agriculture but left for various reasons. The potential biomass that can be grown has been studied to produce bioenergy [22]. However, no studies could be found on the potential to cultivate these areas for fiber production, while it does seem like a promising solution. Not using the current cropland will make it easier to implement the EU Bioeconomy goals without harming the goals of the Farm to Fork Strategy. In addition, the goals of the Biodiversity Strategy will have to be considered. To study it is still possible to produce the demand for synthetic textiles in the EU while staying within these boundaries, the extent and the effects of abandonment must be understood.

2.2 Future of abandoned farmland in the EU

Abandoned land can result from many different factors, and it does not necessarily mean these lands are not suitable for recultivation. In addition to biophysical reasons, abandonment also occurs because of institutional or socio-economic reasons [28]. For example, the collapse of the Soviet Union in 1991 resulted in a lot of abandoned land because of the withdrawal of government support for agriculture, price liberalization, the disappearance of markets, tenure insecurity, and increasing market competition [28], [29] as well as aging populations and migration to cities [30]. Considering biomass production, these non-biophysical reasons for abandonment are essential because it suggests that these lands could still be suitable for crop production. In some Central and Eastern Europe (CEE) countries, suitable cropland was even more often abandoned than unsuitable land, suggesting that institutional and socio-economic reasons were a more important driver than biophysical factors [28]. According to a satellite-based study by Estel et al. [29], 7.6 million hectares (Mha) of land was abandoned in Europe between 2007 and 2012. In addition, 13.6Mha of land is permanently abandoned in Europe. The distribution of this abandoned land is very uneven: 83.3% of this permanently abandoned land is located in CEE countries, in line with earlier findings [28]. Other hotspots of abandonment are mountainous areas, like the Alps, Pyrenees, and the Caucasus [29]. Moreover, this abandonment is projected to continue, and according to the Joint Research Centre (JRC), around 280 thousand hectares of land will be abandoned yearly [31].

This brings us to the effects of abandonment. In a past report, the JRC defined abandonment as "a cessation of management on the agricultural land which leads to undesirable changes in biodiversity and ecosystem services" ([32], p.20). This phrasing implies that abandonment can only have negative effects, and indeed, many effects of abandonment are not necessarily desirable. Potential adverse effects of abandonment include reduced water availability, higher wildfire risk, soil erosion, loss of agro-biodiversity or cultural landscapes [29]. In addition, during the natural vegetation of abandoned areas, these areas are vulnerable to invasive species [23], [27]. However, abandonment can also have positive effects. Abandonment can cause ecological restoration, increased carbon storage [29], increased vegetation density and biomass, and increased hydrological regulation [27]. Many effects are not uniformly found across areas. Whether they have a positive or negative impact on the local environment depends on the location and scale of the area. For example, while abandonment can result in reduced erosion, there are also instances where abandonment causes erosion. Furthermore, while some species will disappear because of abandonment, others will thrive in the naturally vegetated state that follows abandonment [27].

Recultivation of abandoned areas could alleviate some of the adverse effects of abandonment and provide biomass [22]. In addition, recultivation in Europe could prevent land-use change in biodiversity hotspots, like the Amazon. However, recultivation is also not without negative effects. It can, amongst other things, result in nutrient runoff, sedimentation of waterways, and pesticide poisoning [33]. In contrast to recultivation, some conservationists are lobbying for the rewilding of these abandoned areas. Rewilding is the "passive management of ecological succession with the goal of restoring natural ecosystem processes and reducing human control of landscapes" ([23], p.10). Navarro & Pereira [23] state that giving abandoned areas back to nature will benefit biodiversity and people. While many species would be lost due to abandonment, even more species would be gained, and since many species depend on the existence of others, these increasing species could trigger a cascade. Slowly an ecosystem could be achieved that needs little management to provide much biodiversity, in contrast to other conservation measures that need active management [23].

Moreover, amongst the species that would gain from rewilding are large mammals. These megafauna species would benefit from increased forest vegetation and the rejoining of currently fragmented areas [23]. Not only do these species play an important role in natural trophic networks [27], they can also result in an increase in cultural services, like hunting and tourism. Naturally, there are also challenges to rewilding. The local community might be against it because of negative associations with wild areas and possible conflicts with wildlife [23]. In addition, the potential effect on biodiversity differs between regions. Not every region is suitable for megafauna, as is also found in a study by Van der Zanden et al. [27] that looked at the potential habitat for seven big mammals throughout the EU. Their maps on megafauna habitat show that most areas would provide a suitable habitat for only one species but that there are also areas that could provide a habitat for all seven.

Concluding, both rewilding and recultivation have positive and negative effects. Therefore, combining these two scenarios for abandoned land in a way that mostly captures their positive effects is the challenge we face. By rewilding the abandoned land in areas with a lot of biodiversity potential, much land could be conserved, providing important habitat for many species, and achieving part of the conservation goal of the Biodiversity Strategy. Recultivating the abandoned land outside these areas with crops for fiber production can replace part of the EU demand for synthetic fibers:

mitigating the environmental impacts of synthetic fiber production and contributing to a stronger EU Bioeconomy.

2.3 Bio-based fibers as a sustainable alternative

Reducing our dependence on fossil fuels means that synthetic textile fibers need to be replaced. However, not every non-synthetic fiber is necessarily sustainable. The Mistra Fashion Report states that "conventional cotton fibers need to be replaced since pesticide use and irrigation during the cultivation contributes to toxicity and water stress. Polyester is a synthetic fiber that is questioned due to its (mostly) fossil resource origin and the release of microplastics." ([15], p.8). This means that not only do we need to replace polyester, but we should also replace it with sources that are more sustainable than cotton.

There is not one fiber with the suitable properties to replace all applications of synthetic fibers, so we need an arsenal of alternatives [15], [16]. Replacing these fibers can be done through technical or market substitution [15]. Technical substitution is done through fibers that behave in the same way. In contrast, when the fiber properties do not have to be exactly similar, market substitution can suffice. For some applications of synthetic fibers, like sportswear and swimwear, technical substitution will be necessary. However, the low cost of synthetic fibers [2] suggests that they are also used in applications that do not require their specific characteristics. This notion is supported by the fact that the popularity of synthetic fibers has grown tremendously over the years [2], which shows the fibers themselves have replaced many non-similar fibers.

Many different fibers will be necessary to provide alternatives for synthetic fibers in all applications [15]. It is important to note here that for all fibers, the environmental impact, and thus the extent to which they are sustainable, depends on the raw material used and how and where they are manufactured [16]. Per fiber type, wide impact ranges are found in the literature. This variation means that the following fibers have the potential to be sustainable alternatives but are currently not necessarily always better on all environmental measures.

2.3.1 Natural plant fibers

For some applications, polyester could be replaced by plant fibers and regenerated cellulose fibers. These fibers lack some of the properties of polyester and can thus be used as a market substitution. Currently, the most common source for plant fibers is cotton, but fortunately, many other plant fiber crops are (in general) less environmentally damaging. Together these non-cotton plant fibers make up almost 6% of the total fiber market [18]. Of these fibers, jute is by far the most used. However, this crop cannot grow in the environmental conditions of the EU, but the crops for hemp and linen fibers are. Hemp is produced from hemp tow and linen from flax tow. Both are bast-fibers, which means that the natural fibers of the hemp plant are used [15]. Even though hemp and flax have been around for centuries (31) and flax even since the prehistoric period (32), their total market shares are minimal. The shares are only 0.1% and 0.3% for hemp and flax, respectively [16].

For all these fibers, the environmental impact differs significantly between studies. For example, the estimates of how many kilograms of carbon dioxide equivalent are emitted per kilogram of fiber (also known as the climate impact) vary [16]. Cultivating flax and hemp, like other crops, can sequester carbon in the soil. When this is considered, the climate impact of these fibers can be negative, meaning that the amount of carbon they can sequester is greater than the amount emitted during production. However, when carbon sequestration is not considered, the climate impact can be high.

Some studies even found that flax can have a higher climate impact than cotton, and both hemp and flax can have a greater impact than polyester [16]. Nevertheless, it is difficult to compare these results, as some studies include carbon sequestration, and some do not. It merely shows that it matters how it is measured and that there is no definite answer. A measure that does show a clear advantage of hemp and flax crops over cotton is water depletion [16]. Furthermore, the advantages over polyester are that hemp and flax fibers are biodegradable [12], made from renewable resources, and do not shed microplastics [15].

2.3.2 Regenerated cellulose fibers: lyocell

Hemp and flax can also be used to produce regenerated cellulose fibers (previously called man-made fibers), which use dissolved cellulose from plant materials to create new fibers. They could essentially be made from any source of cellulose, but the most common sources are softwood, hardwood, bamboo, cotton, flax, and hemp [15]. Regenerated cellulose fibers have had a small but steady market share of around 6% [18]. However, 79% of this share is viscose, whose production requires many toxic chemicals. Lyocell, one of the new generation cellulosic fibers, currently accounts for only 4% of the regenerated cellulose fiber market [18], even though the production of this fiber makes it a promising alternative. The process requires fewer chemicals and reuses them, making lyocell fibers more sustainable than viscose [34].

Generally speaking, the substitution of currently popular textile fibers with wood-based fibers could have a positive climate impact, according to a report by the European Forest Institute (EFI) [35]. According to this report, wood-based textiles could even result in an ecological footprint five times smaller than synthetic fibers, provided that the forests are managed sustainably. Sustainable forest management is critical in producing environmentally friendly wood-based fibers because it ensures that the other ecosystem services of the forest, like biodiversity and water regulation, are also being maintained [35].

The biggest European producer of lyocell fibers is the Lenzing Group, which mainly uses European spruce and beech as its cellulose sources [36]. The ratio from wood to pulp is currently around 2.5 to 1 (40%), and from this pulp to fiber around 1 to 1 (100%). Other feedstock sources such as textile waste are increasingly used, but according to Lenzing, these do not provide the same resource efficiency yet [36].

2.3.3 (Bio-)Synthetic fibers: PLA

So far, all these fibers were market substitutions, and they can play an important role in replacing synthetic fibers. However, as the Mistra Fashion report points out, in some applications, the properties of synthetic fibers cannot be replaced by plant fibers, and technical substitution is needed [15], [16]. The bio-synthetic fiber polylactic acid (PLA) can be such a technical substitution since it has many of the same properties as polyester, like glossy appearance [17] and strength [15]. PLA is a so-called bio-based polymer, and it can be created in varying ways. The first method, also called first-generation bio-based polymers, uses naturally occurring polymers directly or with a slight modification. This method has been outperformed by newer methods that produce bio-based polymers through fermentation, chemistry, or directly by bacteria [17].

Currently, the most efficient feedstock sources are rich in sugar or starch, and the most efficient crops for PLA production are corn, sugar beet, and sugarcane [37]. Which of these is most effective in producing PLA depends on location. Generally, a ratio of 1.6 kg of fermentable sugar to 1 kg of fiber is achieved. This ratio makes PLA a lot more efficient than other bioplastics like bio-PE and bio-PET, which use four and five kilograms of fermentable sugar, respectively [37]. Moreover, in contrast to PLA, these two bioplastics are not biodegradable [15], making them less suited for a circular economy. The challenge with bio-based polymers will be to scale up the production of these materials [17], as currently, the share of bioplastics is only 1% of the total polymer market [18].

All these alternatives for synthetic fibers are not perfect, but they can be more environmentally sustainable. Besides, these bio-based fibers will be necessary to achieve a stronger EU Bioeconomy. Moreover, the potential of these fibers to be a sustainable alternative is not only determined by their environmental potential but also by the feedstock availability and process scalability of the fibers [15], [16], which is what will be studied in the next part of this thesis.

3. Methodology

3.1 Method and justification

To answer the research question, both the literature review and the spatial analysis are critical. The literature was needed to understand what bio-based fibers could be produced in the EU and what land type could be used to grow them without directly harming other EU strategies concerning land use. Found was that hemp, flax, lyocell, and PLA all have a potential role in substituting polyester and can be produced from various crops that can grow in the EU. It also showed that abandoned farmland is a potential candidate for land that does not compete with food production and that using this land would not compete with the goals of the Farm to Fork Strategy. Literature was also used to study the goals of the Biodiversity Strategy. However, to see whether abandoned land was still viable for bio-based fiber production when these goals were considered, spatial analysis was needed. This spatial analysis made it possible to study abandoned land per region, exclude parts of this land for the Biodiversity Strategy, and calculate per region how much of the various fibers could be produced. However, for this calculation, the fiber yield had to be known for the various crops, and literature was necessary again.

Considering the EU structure, this combination of a literature review and spatial analysis is very useful. Even though the EU has proposed this EU-wide strategy, it differs per member state how it is implemented. The literature review makes sure that the broader picture can be studied and the goals of the EU are understood. In turn, the spatial analysis visualizes the differences between (and within) the various member states and shows how the overarching goals of the EU would affect these member states locally. This spatial variation means that the results will also be helpful for (sub-)national policymakers since the results can inform them how to implement the EU-wide goals for a stronger bioeconomy locally.

3.2 Study area

Because the strategy for a stronger EU Bioeconomy and the other EU strategies are explicitly targeted at the EU member states, this thesis will be limited to these 27 countries. Some of the databases and geographical data used also provide information on countries within or on the borders of the EU, but only the results of EU member states will be shown.

3.3 Data

3.3.1 Literature review

As said, literature was used for policy inventory and for information on bio-based fibers and fiber yield. First, data was gathered on the goals of the EU Bioeconomy and the Farm to Fork and Biodiversity strategies. This information was found in communications, publications, and web pages of the EC.

Information on potential bio-based fibers and the necessary crops was found in academic literature and industry reports. Academic literature mainly showed the environmental impact of the textile fibers in general, while the industry reports provided practical information on their production. For example, industry reports on PLA production showed that while this fiber could be made from various crops, in practice, mainly corn, sugar beet, and sugarcane are used [37]. The same was found in the production of lyocell, which can be made from any cellulose source but is mainly made from spruce and beech [36].

This practical information narrowed down the crops to hemp, flax, corn, sugar beet, sugarcane, spruce, and beech. A literature study was used again to quantify how much land was needed to cultivate them. One source that provided information on yield crops was the statistics division of the Food and Agriculture Organization of the United Nations (FAOSTAT, [38]). Other sources were found through Google Scholar and VU LibSearch by searching for the words “fiber”, “textile”, “yield”, and “hectare” in various combinations with the seven crops and four fibers. For example, possible searches were “fiber yield hemp” but also “fiber yield flax linen” or “hectare maize PLA”. As many sources as possible were included in the available time, and at least two sources were included for all fiber crops. The final yield ranges were used to calculate potential production. A recent estimate of the annual EU demand by the European Environment Agency (EEA) was used To compare this production with the EU demand for synthetic fibers [4].

3.3.2 Spatial data sources

Various spatial sources were used for the analysis in QGIS (Table 1.). The environmental stratification [39] was used for the environmental zones, as these present detailed environmental changes throughout Europe. For EU borders, the most recent information was used on NUTS level 0 [40]. For the distribution of crops, various sources were used. For hemp & flax, the LUCAS survey data [41] was used. For all PLA crops (corn, sugar beet, and sugarcane), the MAPSPAM crop production maps [42] were used. Finally, for both lyocell crops (spruce and beech), the tree species maps of the European Forest Institute (EFI) [43] were used.

The abandonment map of Estel et al. [29] was used to analyze the abandoned land per region. A simplified version was used of the Natura 2000 map of the EEA [44] to discard lands within protected areas. Information on potential megafauna habitats was collected from Van der Zanden et al. [27]. And for rivers, the water bodies and watercourses classifications were used of the CORINE land cover maps [45].

Table 1. Spatial data sources

Data		**Scope**	**Year**	**Resolution**	**Source**
Crop & tree species distribution					
Hemp	Hemp	EU	2015	2km [1]	LUCAS [41]
Linen	Flax				
PLA	Corn	Global	2019	10km	MAPSPAM [42]
	Sugar beet				
	Sugarcane				
Lyocell	Spruce	Europe	2011	1km	Brus et al. (2011) via EFI [43]
	Beech				
Distribution abandoned land & potential biodiversity regions					
Abandoned land		Europe and surroundings	2015	~273m	Estel et al. [29]
Megafauna habitat		EU	2017	1km	Van der Zanden et al. [27] via [46]
Rivers		Europe and surroundings	2018	100m	CORINE [45]
Protected areas (Natura 2000)		EU	2019	1km [2]	EEA [44]
Geographic information					
Environmental stratification		Europe and surroundings	2018	1km	Metzger (2018) via University of Edinburgh [39]
NUTS regions		Europe	2021	1:1Mio	EUROSTAT [40]

[1] The resolution of the LUCAS data is based on the notion that the land survey is done along data points at every 2 km. [2] The actual resolution of the Natura 2000 data is finer, but a map with a coarser resolution of 1km was used because of limited computational power.

3.4 Analysis

3.4.1 Fiber yield

A literature review of academic literature and industry reports is done to estimate the yearly fiber yield per area for every crop type (kg/ha) (Figure 1.). For the FAOSTAT database [38], an average of European crop yield is calculated for the most recently available years (2017-2019). When sources only provided part of the necessary information and not the total yield, information from other sources was used to calculate this. This process resulted in a range for every crop type with a minimum, median, and maximum yield.

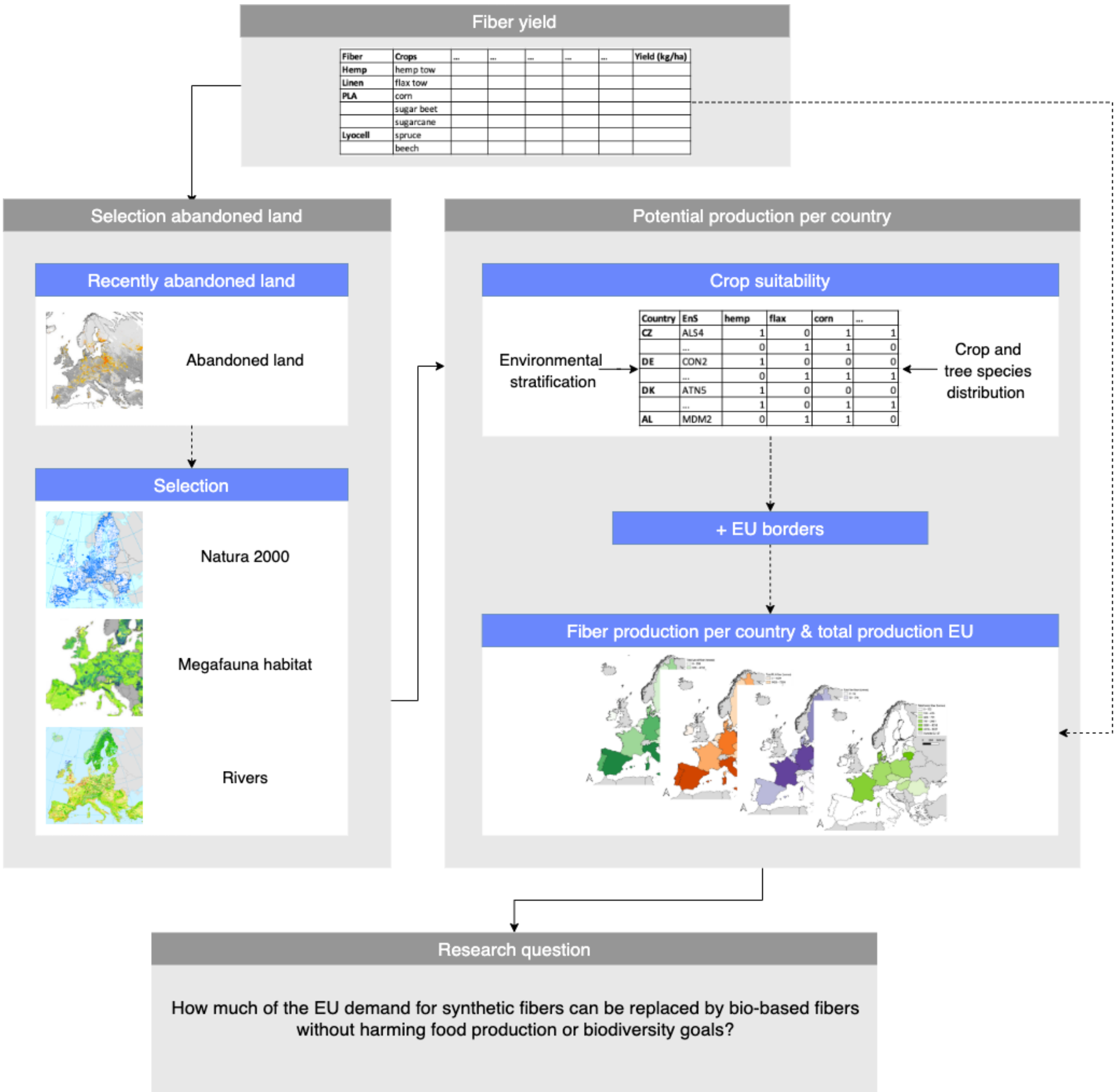

Figure 1. Methodological framework

3.4.2 Selection abandoned land

The total amount of abandoned land (ha) per region was measured using the abandonment maps from Estel et al. [29], using one of their definitions of abandoned farmland: farmland that was actively used between 2001 and 2006 for at least four years and abandoned for at least five years between 2007 and 2012. After the total abandonment is analyzed, part of this abandoned land is excluded from further analysis to accommodate for the goals of the Biodiversity Strategy. This selection was made by excluding abandoned land located within Natura 2000 regions [44], potential megafauna habitat for more than two species [27], or rivers [45] (Figure 1.).

Subsequently, a buffer of 5km is placed around these areas like the method proposed by Meyfroidt et al. [47]. This excludes abandoned land close to these potential biodiversity regions, combats fragmentation between these regions, and makes room for the proposed river restorations. The abandoned land within these buffer areas was also excluded from further analysis.

3.4.3 Potential fiber production in EU member states

Per environmental zone, suitability for growing the various crop types was checked using the various sources of crop production. For hemp and flax, this was done by checking whether these crops were mentioned in the data points of land survey data. If a particular point mentioned hemp or flax production, the environmental zone wherein that point was located was defined as a suitable region for that crop. For the PLA and lyocell crops, every area with a production level of more than zero was defined as a suitable region. Then, this data was used to identify all environmental zones according to their suitability to grow the various crop types (1) or not (0) (Figure 1.).

After this classification, the environmental zones were split by EU borders to calculate the results per EU member state (Figure 1.). This split was deliberately done after the suitability per region has already been identified because environmental conditions determine which crops can grow and not land borders. For these regions, the final selection of abandoned land was checked. The total area of abandonment per region (ha) is then divided by the number of suitable crops in that region to ensure that all available land is only used once and promote the use of as many crops as possible. Then the yield ranges (kg/ha) were used to calculate how much fiber (kg) could be produced on these areas (ha). Per country, the potential production of the various environmental regions was added up to provide the potential fiber production per EU member state (Figure 1.).

In this calculation, PLA fiber is favored over lyocell, and this is in turn favored over hemp and linen because of the number of crops per fiber. If a region is suitable to grow all seven crops, 3/7 of the abandoned land goes to the production of PLA, 2/7 to lyocell, and 1/7th to both hemp and flax. This order reflects their average yield and their ability to substitute synthetic textiles and results in as much crop diversity as possible while maintaining a high yield.

3.4.4 Total potential compared to demand

The total annual demand for synthetic fibers in the EU is 3.66 million tons [4]. After the EU’s total production potential was calculated, this was compared to this annual demand to understand how much of the synthetic fiber demand could be replaced under the minimum, median and maximum yield scenarios (Figure 1.).

4. Results

4.1 Fiber yield

The information on fiber yield per hectare differed significantly between the various sources used. Therefore, with the FAOSTAT crop data, an average was calculated. The other sources were not available over multiple years, and thus multiple sources were used per crop to reflect this variation (Table 2.). The type of information that was provided by the sources also differed. Some sources gave an exact estimation of fiber yield per hectare, and others gave a range of yields. Furthermore, some sources did not give an exact fiber yield but merely provided the information with which it could be calculated what the yield would be. For example, one source only gave the dry and wet weight yields per crop and the component of fermentable sugar (%) [48]. Information from other sources was used to calculate how much fiber this would be per area. In this specific example, information about the conversion rate from fermentable sugar to fiber [37] was used. This method ensured a minimum,

Table 2. Yield ranges per fiber and crop type

Fiber	Crop	Source	Yield (kg/ha/yr)	Dry weight (kg/ha/yr)	Fermentable sugar (%)	Conversion to fiber	Fiber per area (kg/ha/yr)	Total range (kg/ha/yr)
Hemp	Hemp	FAOSTAT [38]	3739				[1] 748 - 1122	748 - 5000
		Lips et al. [49]	8000				1920	
		Duque Schumacher et al. [50]	4000-20000			20-30%	1000 - 5000	
		Van der Werf & Turunen [51]	8000				1041 - 2073	
Linen	Flax	FAOSTAT [38]	3979				[1] 995	995 - 2200
		Lips et al. [49]					2200	
		Van der Werf & Turunen [51]	6000				[1] 1500	
		Salmon Minotte & Franck [52]				25%	1566	
PLA	Corn	FAOSTAT [38]	7051				[1] 2641	2641 - 4800
		Davies & Vink [53]			57.2	2.67kg corn /1kg PLA	[1] 2641	
		Bos et al. [48]	10630	7440	75.0		[1] 3488	
		Corbion [37]				1.6kg sugar /1kg PLA	4800	
	Sugar beet	FAOSTAT [38]	60413				[1] 5236	5326 - 9100
		Bos et al. [48]	75000	20000	52.0		[1] 6500	
		Corbion [37]				1.6kg sugar /1kg PLA	9100	
	Sugarcane	FAOSTAT [38]	75735				[1] 7992	7809 - 8300
		Bos et al. [48]	74000	17000	73.5		[1] 7809	
		Corbion [37]				1.6kg sugar /1kg PLA	8300	
Lyocell	Spruce	Shen & Patel [54]	4020				1471 - 5556	1471 - 5556
		Lenzing [36]				40%	[1] 1608	
	Beech	Shen & Patel [54]	4247				1471 - 5556	
		Lenzing [36]				40%	[1] 1699	

[1] When the information on fiber per area was not directly cited by the source it was calculated with the information from other sources to provide an estimate (Table A1.).

median, and maximum yield estimation for all fiber crops. For further analysis, this whole range of fiber yield estimations was taken to represent the variation. The minimum, maximum, and median results are calculated for every step, even though they are not always shown in the following tables and graphs.

The highest median fiber yield is found for sugarcane (*Mdn:* 8005 kg/ha), followed closely by another PLA fiber, sugar beet (*Mdn:* 7213 kg/ha). The third highest-fiber yield is also a PLA fiber: corn (*Mdn:* 3721 kg/ha). Followed by lyocell fiber made from spruce or beech (*Mdn:* 3514 kg/ha), hemp fiber made from hemp (*Mdn:* 2874 kg/ha), and lastly, linen fiber made from flax (*Mdn:* 1598 kg/ha). The most significant variation in yield is found for hemp and sugar beet. The smallest variation is found for sugar cane.

4.2 Selection abandoned land

In total, the amount of recently abandoned land that was measured in the 27 EU member states was more than 1.7 million hectares (Mha) (Tabel 3.). The subsequent selection of abandoned land based on the proximity to potential biodiversity regions resulted in most land being excluded. After selection, only 0.25Mha is left of the total 1.7Mha abandoned land. This means that only 13.7% of the measured abandoned lands were outside or more than 5km away from Natura 2000 regions, rivers, and potential megafauna habitats. Still, this means that almost 250 thousand hectares of abandoned land could be used for recultivation without directly harming the goals of the Farm to Fork Strategy and the Biodiversity Strategy.

The close-up examples do not provide a quantitative result but are merely shown as a visualization of the selection process (Figure 2.). Figure 2A shows abandoned land around a river. Figure 2B shows abandoned land around a combination of Natura 2000 areas and potential megafauna habitats together. And Figure 2C shows an area mainly covered with potential megafauna habitat and some small Natura 2000 sides. All examples show that the 5 km buffer placed around these areas excluded abandoned land that is close to them and leaves room for biodiversity measures.

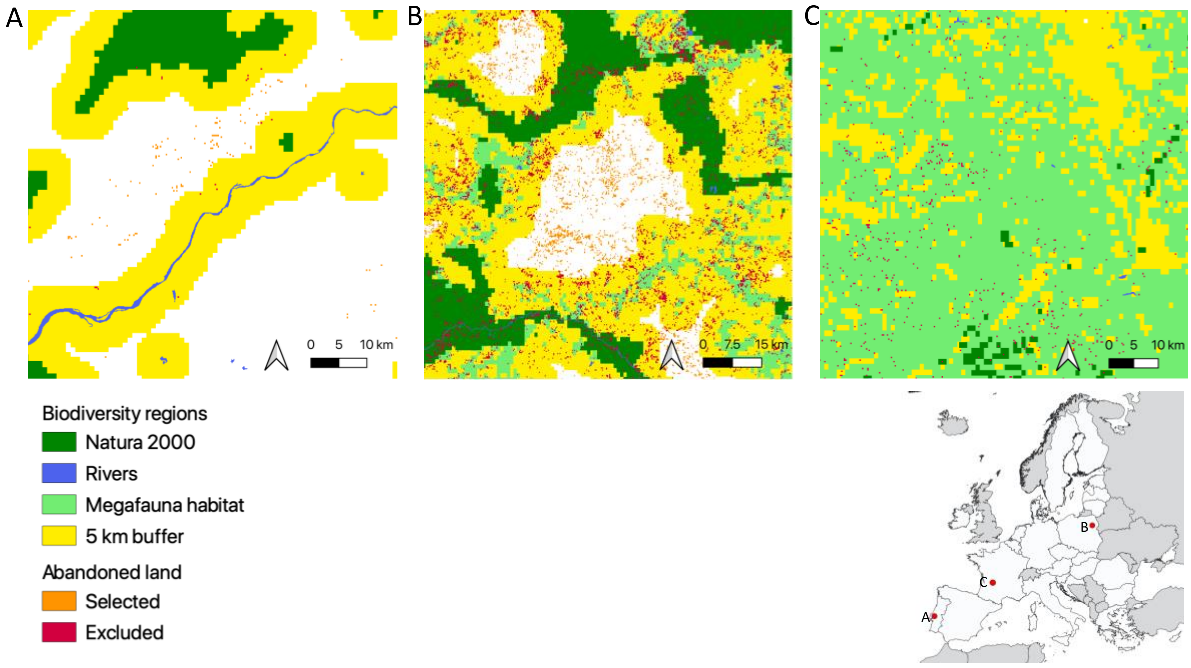

Figure 2. Close-ups of selection process

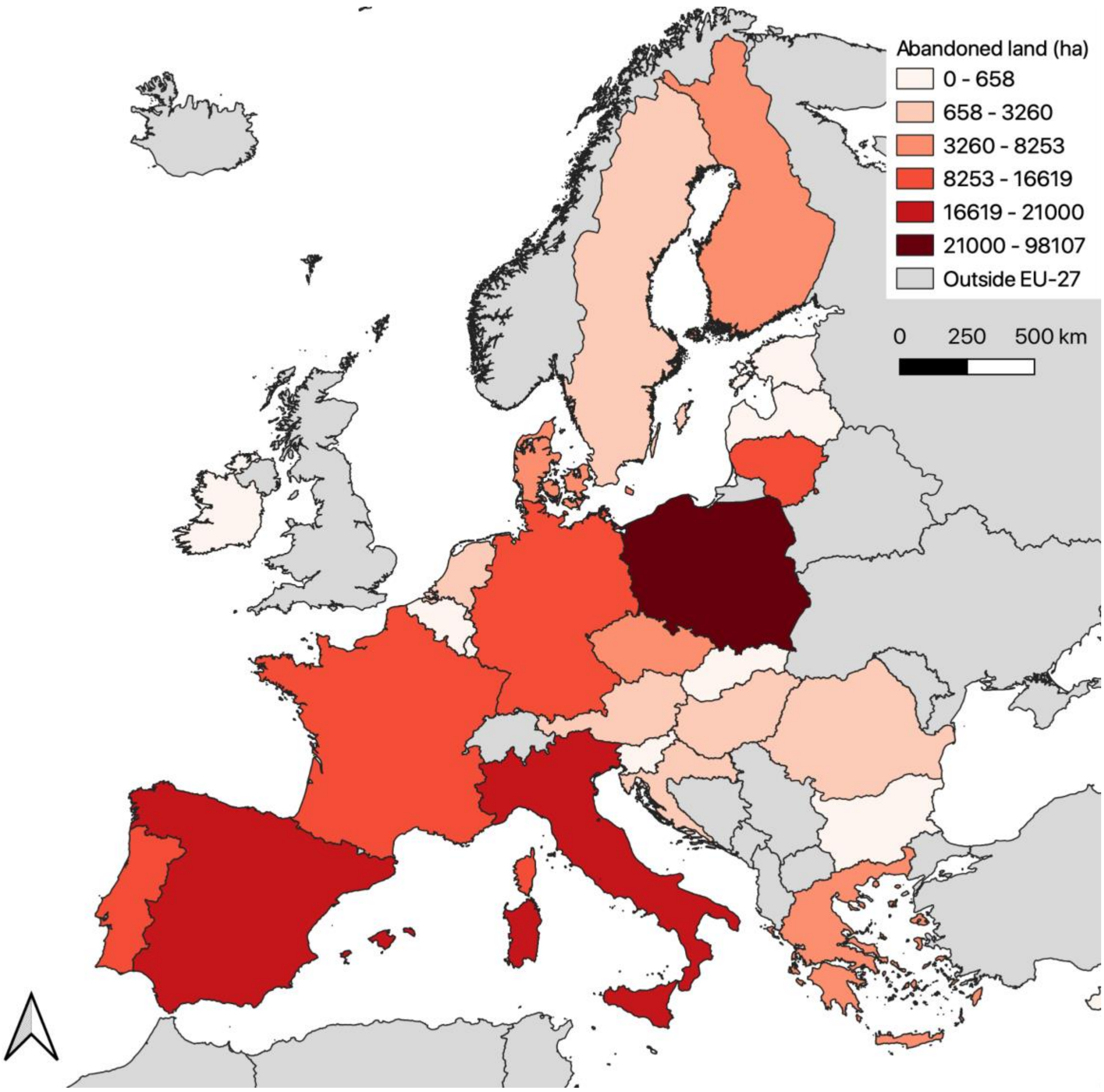

Figure 3. Abandonment per EU member state

There are clear differences in the effects of selection since it differs per country where the abandoned land is located and how many Natura 2000 areas, rivers, and potential megafauna habitats there are. This effect is seen when the difference between the total and the selected amount of abandoned land is examined. Table 3. shows how the selection process has affected how countries compare to each other in the amount of land available for recultivation. Countries that lose many abandoned lands through the selection move down in the ranking of available land, and countries that lose relatively little land move up. For example, 95% of the abandoned land found in Germany and France was inside or close to potential biodiversity regions. As a result, these two countries drop four places in rank after the selection process: from the second and third to sixth and seventh place. An example of a country where the selection improved how the available land compares to other countries is Portugal. More than 38% of the total abandoned land is outside or further than 5km away from potential biodiversity regions, so this country moves up from tenth to fifth place. Figure 3. shows the distribution of this selected land for all 27 EU member states.

How much of the abandoned land is left after the selection differs per EU member state (Figure 3., Table 3.). The most abandoned land is found in Poland (981.1 km²), followed by a long shot by Italy and Spain (210.0 & 206.1 km² respectively).

There are two countries where the selection process of abandoned land resulted in no suitable abandoned land. In Luxembourg, 23.5 km² of abandoned land was measured, but because the whole country is covered with Natura 2000 and potential megafauna regions, no abandoned land was selected. The same holds for Malta, where the 3.1 km² of abandoned land is lost after selection because of the proximity to Natura 2000 regions.

Table 3. Abandoned land per EU member state before and after selection

EU member state	Abandoned land before selection (km²)	Ranking	Excluded through selection (%)	Abandoned land after selection (km²)	Ranking
Poland	5047	1	80.6	981	1
Germany	2674	2	94.3	151	6
France	2301	3	95.0	115	7
Spain	1186	4	82.6	206	3
Italy	1034	5	79.7	210	2
Lithuania	895	6	81.4	166	4
Finland	553	7	90.9	50	11
Czech Republic	485	8	86.2	67	10
Sweden	478	9	93.7	30	13
Portugal	393	10	61.3	152	5
Greece	386	11	79.0	81	9
Austria	342	12	92.0	27	15
Romania	289	13	91.7	24	16
Denmark	268	14	69.2	83	8
Hungary	238	15	86.3	33	12
Slovakia	234	16	97.2	7	18
Latvia	202	17	97.8	4	19
Netherlands	169	18	87.7	21	17
Estonia	157	19	98.8	2	24
Ireland	137	20	97.7	3	21
Croatia	129	21	78.7	28	14
Belgium	96	22	96.7	3	22
Slovenia	83	23	97.0	2	23
Bulgaria	64	24	94.5	4	20
Luxembourg	24	25	100.0	0	26
Cyprus	6	26	98.7	0	25
Malta	3	27	100.0	0	27
Total	17872 km²		86.3	2450 km²	

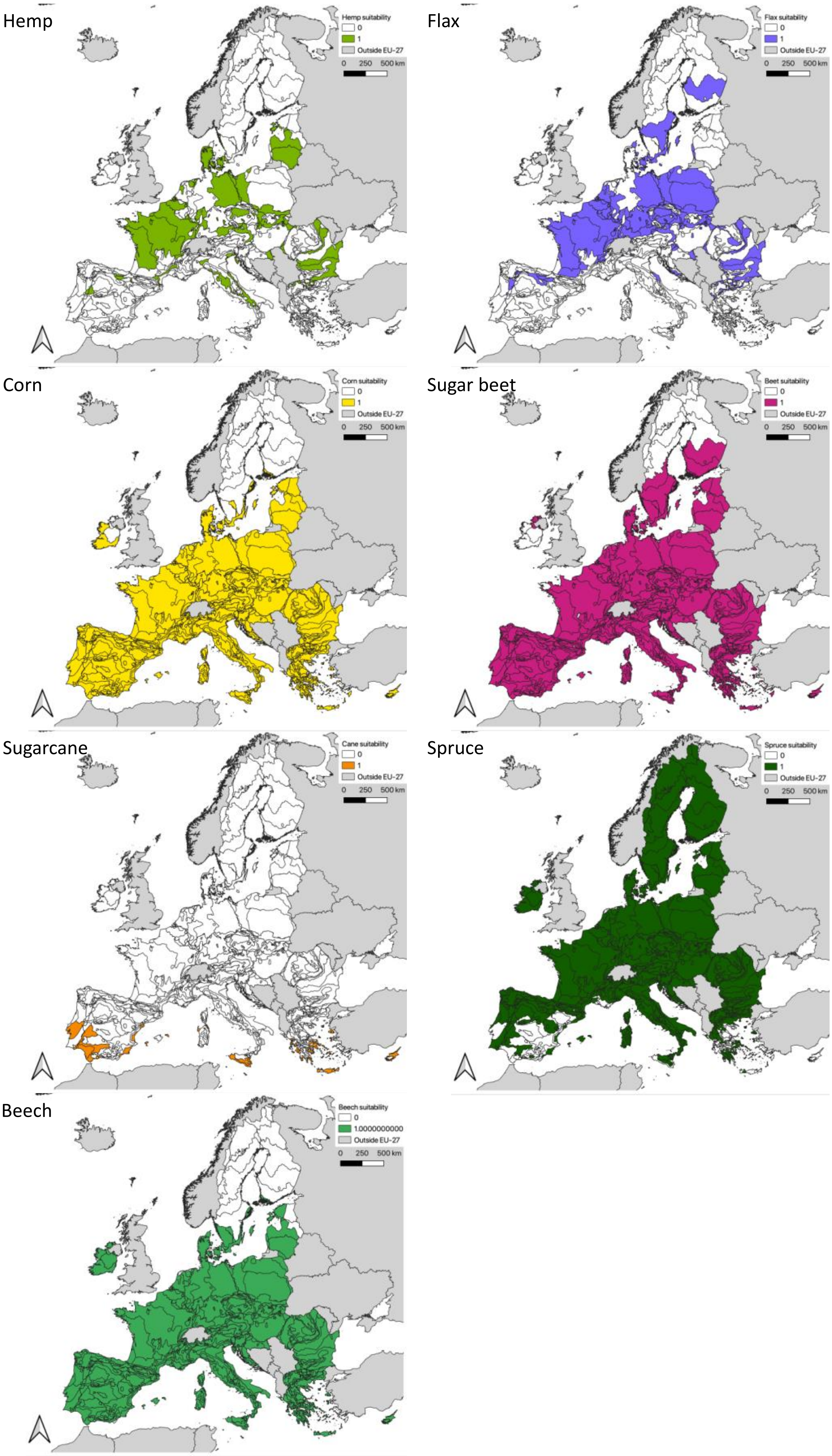

Figure 4. Crop suitability of the environmental zones

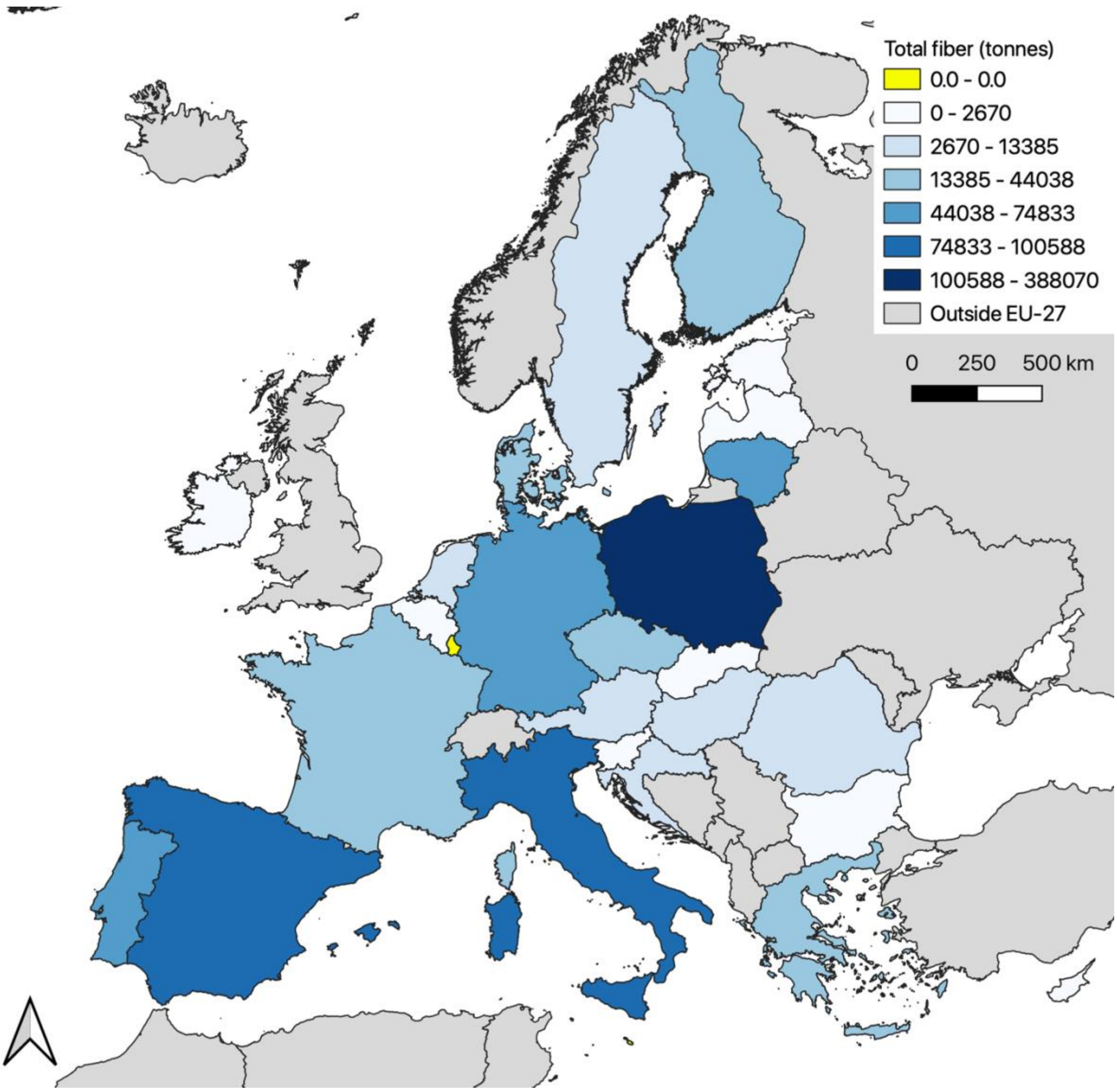

Figure 5. Median fiber production per EU member state

4.3 Potential fiber production in EU member states

The seven crops show a different distribution across the environmental zones (Figure 4.). Sugarcane is the least widespread of all the crops; it is only found in some of the most Southern environmental zones of the EU. Hemp and flax only grow in some of the Northern and middle zones. Both corn and sugar beet are found almost everywhere. Spruce and beech show an exactly reversed pattern. The only regions unsuitable for beech production are in the Northern parts of the EU, while the only regions unsuitable for spruce production are in the South (Figure 4.).

After selection, the three countries with the most abandoned land (Poland, Italy, and Spain) are also the top 3 countries in potential fiber production (Figure 5.). Poland can produce the most fiber (Mdn: 388070t, minimum: 235623t, maximum: 540518t). The second and third biggest potential producers are Italy (Mdn: 100588t, minimum: 66116t, maximum: 135060t) and Spain (Mdn: 100066, minimum: 67083, maximum: 133049) respectively (Table 4. shows the median production. Minimum and maximum values can be found in Table B1.).

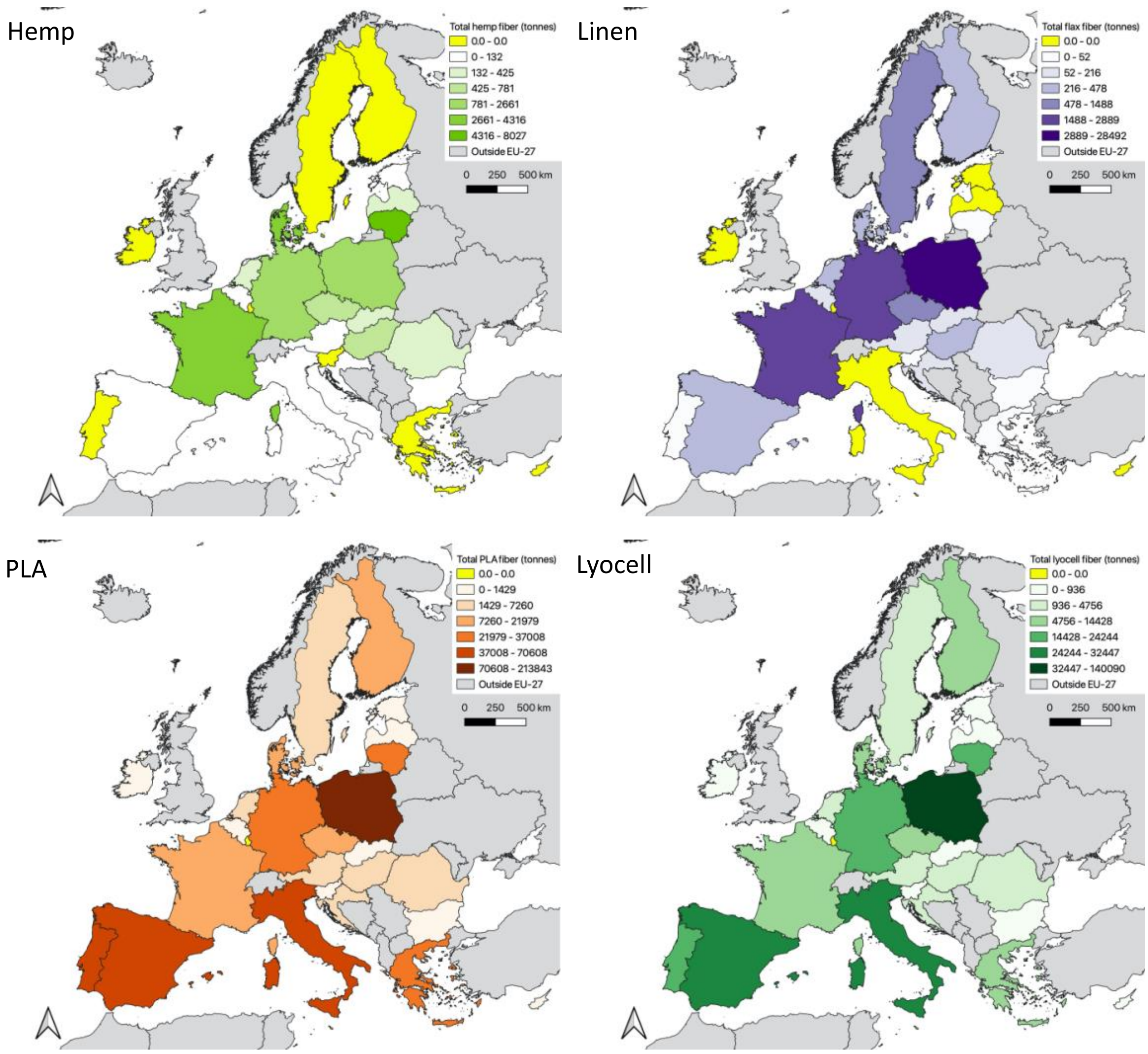

Figure 6. Production potential of the various fibers per EU member state

This top 3 is followed by Portugal, Lithuania & Germany. Independent of which production level is chosen (minimum, maximum, or median yield), these top 6 countries together already produce over 75% of the total potential fiber production. Lower production but still accounting for a median yield of over 13000 tons are France, Denmark, Czech Republic, Finland & Hungary. There are two countries where the selection of abandoned land resulted in no suitable abandoned land: Luxembourg & Malta. Therefore, Luxembourg has zero fiber potential, even though all fibers except for sugarcane can grow here (Figure 4.). The same is true for Malta, even though this country would be suitable to grow all PLA crops (corn, sugar beet, and sugarcane) and beech.

The potential is not only determined by the amount of available land but also by the types of fiber that are suitable to grow in that region. Lithuania has more abandoned land than Portugal (Table 3.). However, Portugal has a higher total fiber potential because Portugal contains environmental zones suitable for sugar cane, which has the highest yield of all studied crops. Lithuania and most other countries are not suitable for sugarcane, lowering their potential production.

Table 4. Median fiber yield per EU member state

Country	Total fiber (tonnes)	Country	Total fiber (tonnes)
Poland	388 070	**Croatia**	11 996
Italy	100 588	**Romania**	10 138
Spain	100 066	**Netherlands**	8 552
Portugal	748 33	**Slovakia**	2 670
Lithuania	700 35	**Latvia**	1 838
Germany	620 62	**Ireland**	1 456
France	440 38	**Bulgaria**	1 432
Greece	431 04	**Belgium**	1 210
Denmark	339 52	**Slovenia**	1 034
Czech Republic	268 84	**Estonia**	871
Finland	257 59	**Cyprus**	42
Hungary	133 85	**Luxembourg**	0
Austria	121 39	**Malta**	0
Sweden	120 38		

Table 5. Total production potential compared to demand

Results	Minimum yield (tonnes)	Median yield (tonnes)	Maximum yield (tonnes)
Hemp	6 184	23 762	41 340
Flax	24 472	39 290	54 108
PLA	474 222	634 661	795 099
Lyocell	146 736	350 480	554 224
Total	651 614	1 048 193	1 444 771
% of EU demand for synthetic textile fibers	18	29	39

Looking at production potential of the various fibers, Poland has the most potential for linen, PLA, and lyocell (Figure 5.). For hemp, the most potential is found in Lithuania. This country ranked fourth in the total amount of selected abandoned land (Table 3.), but all environmental zones in this country are suitable to grow hemp (Figure 3.). Hemp is also the fiber of which the potential production is the least widespread of all fibers. PLA and lyocell can be produced almost everywhere, although this also results from the fact that they can be produced from more than one crop. If an environmental region is not suitable for one of the crops, it might still suit the other. Therefore, essentially all countries with more than zero abandoned land have the suitability for producing PLA and lyocell (Figure 5.)

4.4 Total potential production compared to demand

The yearly demand for synthetic textile fibers in the EU is 3.66 million tons [4]. Looking at the various yield scenarios, this means that at best 39% and at worst 18% of the total demand can be substituted by bio-based fiber production (Table 5.). In the median yield scenario, 29% of the EU demand for synthetic fibers can be replaced. Most of the total production is made up of PLA production.

5. Discussion

5.1 Interpretation of results

The findings demonstrate that when other EU goals are considered, the potential to produce bio-based products becomes a lot smaller. This is in line with previous papers that already stated that the production of bio-based products is constrained by land use [21]. It also challenges the notion of the EU that the various areas covered by the EU Green Deal are mutually enforcing [20]: the land that is needed for the EU green deal strategies directly affects the cropland expansion that is needed for the EU Bioeconomy.

However, the results also show great potential. All studied fibers currently have a total market share smaller than 1% [18]. As mentioned in the Mistra Fashion Reports, the sustainability of a fiber type is also determined by the feedstock availability and the process scalability [15], [16]. This thesis shows that the feedstock availability can be increased by using abandoned land as a land source, making EU-based production of the fibers scalable. Even though more than 85% of abandoned land is excluded by the strict selection process based on the proximity to potential biodiversity regions, the results show that around 1 million tons of bio-based fibers could be produced. This is about a third of the total EU demand for synthetic fibers. These bio-based fibers can reduce the dependence on non-renewable resources, limit some of the fashion industry's environmental impacts [12], [15], [16], [35], and mitigate some of the already emitted carbon dioxide emissions through carbon sequestration [44]. Moreover, since the EU currently imports almost half of its synthetic fiber demand from other countries [4], the production can create jobs and strengthen European competitiveness. By using only abandoned land and no current cropland, and in turn, selecting only those pieces of abandoned land that are not close to potential biodiversity regions, this is done without directly harming the goals of both The Farm to Fork and the Biodiversity strategy. Therefore, this production also achieves the first two goals of the EU Bioeconomy: to ensure food and nutrition security and manage natural resources sustainably [19].

Moreover, the spatial analysis shows that the potential to produce bio-based fibers is not evenly distributed amongst the EU. Poland has by far the most potential in producing bio-based fibers on abandoned land without harming food production or biodiversity regions. This finding aligns with other studies that found Poland was one of the main hotspots of abandonment [29] and will be in the future [55]. Poland is followed by Italy, Spain, Portugal, Lithuania, and Germany. Since these six countries already make up 75% of the measured potential production, the EU could focus their efforts on bio-based fiber production mostly on these countries. Especially since, like Poland, the other top 6 countries are also projected to be at high risk in the future for more abandonment [31], [55].

The environment in Europe is not uniform, which was already reflected in the 84 zones with different environmental conditions described in the environmental stratification of Europe [39]. When these zones were combined with the available crop distribution datasets, it became apparent that some crops are more suitable for a wide range of environmental conditions than others. Sugarcane, for example, can only be cultivated in the most Southern parts of Europe. This aligns with the fact that sugarcane thrives in warmer regions [37]. The spatial analysis also suggests that hemp production is limited to a small number of environmental regions. However, when the growing conditions of that fiber are considered, more environmental regions should be suitable for production. Hemp can grow in various soil types, under many different environmental conditions, and in a range of temperatures [50]. The limited distribution of hemp can, therefore, better be explained by past legislation. For a long time, the production of industrial hemp has been hindered by EU legislation regarding the THC content. Until recently, hemp with a THC content higher than 0.2% was considered marijuana and thus not legal to grow [56]. Fortunately, a bill was passed by the EU parliament to make it easier to produce industrial hemp, and in the latest revision of the CAP, the allowed THC content was increased to 0.3%. This threshold is more in line with research on industrial hemp and marijuana characteristics and makes the production of certain high-yield hemp strains easier [56].

5.2 Limitations

Of course, there were various limitations in the methodology of this study. The estimates of fiber yield found in the literature are widespread, which can be explained by the many things that influence crop yields like rainfall, temperature, soil climate, humidity, and sunshine. This thesis tried to reflect that variability with the three yield scenarios (minimum, median, and maximum yield). These scenarios provided three distinct estimates of what kind of production we can expect. However, it is not realistic that all crops and regions are in one of these scenarios at the same time. More likely, some regions and some crops will provide the maximum yields, while others will provide the minimum or median. Future research could include local crop suitabilities to give a more exact estimate of the crop yields. For example, local crop yield estimates could be based on data from the Global Agro-Ecological Zones (GAEZ) database, which calculates agricultural suitability and yield potential based on climate, soil, and terrain conditions [57].

Another limitation is the extent of abandoned land. As other papers already discussed, abandoned land is complicated to measure. There are multiple definitions of what abandoned land is, and even with a clear definition, the heterogeneous abandonment patterns make it difficult to identify them [29]. As described earlier, there are many different reasons for abandonment [28]–[30]. In addition, there are differences in the natural vegetation of the abandoned land, which can be vegetated by herb, shrub, or forest, complicating the detection on satellite images. Moreover, the abandonment can both be very sudden or gradual, complicating the detection of differences over time [29].

This thesis was entirely based on the abandonment maps of Estel et al. [29], which used three definitions of abandonment to reflect the debate around the exact definition. For simplicity, this study focused on one of these definitions since the results were already complicated by the wide ranges of fiber yields found in the literature. However, this meant that the nuance Estel et al. [29] provided by including multiple definitions was lost. A follow-up study could focus their efforts on the top 6 of the fiber-producing countries and look at the various definitions in more detail. Furthermore, even though the classified abandonment maps, compared to other papers [28], had a very high overall accuracy of 90.1%, they only provide a snapshot of a couple of years. The maps of abandoned land provide information on recently abandoned land and do not reflect all abandoned land in the EU, which might be more than is now suggested. It is hard to find exact information on the extent of agricultural abandonment in Europe. All available information is merely a snapshot because abandoned land might be recultivated again in the following years, while other lands might be abandoned. That said, the total amount of abandonment measured during the studied six years (1.7Mha) is almost exactly what the JRC estimated. They concluded that around 280 thousand hectares would be abandoned each year, meaning that over six years 1.68Mha of land is expected to be abandoned [31].

In addition to varying abandonment, the limited durability of the results is also caused by changing crop suitability and fiber innovations. As said, changes in legislation might affect hemp suitability in the following years. Moreover, climate change might have a significant effect on crop suitability.

However, the results on specific crops are difficult to project and depend on the specific context. For example, the projected increase in droughts could harm sugarcane yield, but a reduction in frost events could positively impact yields [58]. Because of these varying impacts, it remains to be seen how climate change effects will impact the studied crops in the following years. Therefore, the estimation of crop production needs to be regularly updated. In addition, clothing fiber innovations underline the importance of regular follow-up studies as well. New alternative fibers are emerging and are made of the most surprising resources, like seaweed and citrus peel [15]. This thesis was limited to fibers already established on the market, but many more candidates might soon need to be included in the analysis.

Outside the scope of this thesis was the third goal of the Biodiversity Strategy: planting 3 billion trees [26]. The exact plans of the EU to achieve this goal are not yet published, and as of now, it remains unclear whether these 3 billion trees can also be planted as plantations or semi-natural forests and used for timber and wood pulp production. If that is the case, the production of lyocell fibers can directly contribute to this goal. Considering the findings of the European Forests Institute report, these forests can also provide other ecosystem services in addition to providing timber [35]. However, because rewilding forests also has certain benefits [23], it would be advisable to not achieve the goal entirely by planting these non-natural forests and also let parts of the planted forest rewild.

5.3 Implications

This leads us to the implications of the thesis. If the potential fiber production is to be obtained, the rate of recultivation must increase. The rate of recultivation in abandoned areas is currently shallow [31]. However, the annual maps of Estel et al. [29] do show that recultivation is slowly becoming more apparent. A case study in Ukraine showed that crop suitability and accessibility are factors that can increase recultivation [30]. According to the researchers, these findings can be used to inform local and EU policymakers. They state that accessibility could easily be improved by improving infrastructure. Concerning crop suitability, they state that the government should implement "targeted policies, with agricultural policies aiming at regions with favorable environmental conditions for agriculture, and policies fostering afforestation and thus carbon sequestration and other non-provisioning services aiming at marginal agricultural land close to existent forests" ([30], p. 79).

Policy efforts of the EU can mainly be targeted at the top 6 countries since these together already produce 75% of the measured potential. In addition to improving infrastructure, there are various other things that the EU and the local government could do to improve bio-based fiber production in these high-potential countries. Not only cropland but biorefineries to produce fibers are needed to create local bioeconomies in these countries. In Lithuania, there are currently zero fiber biorefinery plants [59]. Poland also has no commercial fiber biorefineries, although there is one pilot plant. Spain has three commercial plants and two pilot plants, Italy has one commercial plant and seven pilots, and Portugal has four commercial plants. Of these top 6 countries, only Germany already seems to have a viable number of fiber biorefineries, with 27 commercial plants, two pilots, and five Research & Development centers [59]. A straightforward way to produce more bio-based fibers and achieve a stronger EU bioeconomy would be to help these countries develop new biorefineries for fiber production.

Germany already has many biorefineries that can produce fiber and pulp, which is also in line with other research that shows France & Germany currently have the strongest bioeconomies [60]. Because of this advanced position, Germany could take the lead in getting the other top 6 countries to their level of production. German policymakers and industry stakeholders can help the other countries with developing more commercial plants. Moreover, the five Research & Development plants already available in Germany could have a significant role in EU Bioeconomy's future. They can use it to investigate other feedstock sources for bio-based fiber production, like food waste and agricultural residues. Interestingly, France falls just out of the top 6 of potential fiber production. Even though it ranked third in the total amount of abandoned land, the selection on biodiversity regions excluded around 95% of all abandoned land and thus lowered the potential fiber production.

Another important note is that the fibers must be produced in the most sustainable way to be a sustainable alternative to polyester. There is no perfectly sustainable fiber as it always depends on how the fiber is manufactured [15], [16]. For example, only 0.5% of the flax cultivated is certified as organic [18], and increasing this number could improve the environmental impact of this fiber. Not only do the fibers have to be produced responsibly, but they also must be implemented by the fashion industry. If they must indeed be a replacement, clothing manufacturers must show a willingness to use these bio-based fibers instead of synthetic ones. Reasons for the manufacturers to keep using these synthetic fibers are their low cost and their specific characteristics. However, because of carbon pricing and reduced availability of fossil fuels, their price might increase, increasing the industry's willingness to look at replacements. Secondly, even though synthetic fibers have many unique qualities, the bio-based fiber PLA is almost similar to polyester, and it might even outperform this fiber in the future [17]. The EU could also incentivize the industry to use bio-based materials by supporting businesses that want to implement them in their production.

However, even in the best scenario where maximum yield is achieved for all fibers, 61% is left of the EU demand for synthetic fibers. This shows that if the EU truly wants to replace all synthetic fibers, they must also focus on other options. Fortunately, other options to replace these unsustainable fibers are already found in the Circular Economic Action Plan: reducing the demand for clothing and reusing and recycling the already made clothes [20].

6. Conclusion

The results show that the ability to achieve EU Bioeconomy goals is hampered when the goals of the Farm to Fork and the Biodiversity Strategy are considered. Because they all rely on land use, achieving one of them constrains the other. As a solution to this problem, this thesis studied abandoned farmland, which is increasingly found across the EU. Recultivating this land has the potential to produce some of the needed bio-based fibers without harming food production. However, conservationists are lobbying for the rewilding of this land to increase biodiversity, and according to our analysis, most of the abandoned land measured would be suitable for that purpose.

The crops for hemp (hemp), linen (flax), PLA (corn, sugar beet, and sugarcane), and lyocell (spruce and beech) differ in how much fiber can be produced from them. Sugarcane has the highest median yield and hemp the lowest. While hemp, linen, and lyocell can be used for market substitution, only PLA can be a technical substitute for synthetic fibers.

Growing the seven crops on abandoned land that is not within or in proximity to biodiversity regions, producing bio-based fibers without harming food production or biodiversity goals is possible. With this production, around 29% of the total demand for synthetic fibers can be replaced. Poland harbors the most abandoned land by far. It also has the most significant potential for fiber production.

Together with the other top 6 countries (Italy, Spain, Portugal, Lithuania, and Germany), it can produce 75% of the potential production.

Therefore, it is recommended that the EU mainly focuses its efforts on these top 6 countries. It can do so by helping the development of biorefineries and improve infrastructure. Moreover, the fashion industry must also be incentivized to use bio-based materials. Carbon pricing might have a role here since this could increase the price of synthetic fibers, lowering their economic advantage over the other fibers. However, since only around a third of the synthetic fiber demand can be replaced, the EU must also focus on other efforts such as reducing, reusing, and recycling textile fibers.

7. Acknowledgments

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Appendix A Fiber yield calculations

Table A1. Fiber yield calculations

Fiber	Crop	Source	Yield (kg/ha/yr)	Dry weight (kg/ha/yr)	Fermentable sugar (%)	Conversion to fiber	Fiber per area (kg/ha/yr)	Calculation
Hemp	Hemp	[38]	3739				[1] 748 - 1122	3739 * 0.20 - 3739 * 0.30
		[49]	8000				1920	-
		[50]	4000-20000			20-30%	1000 - 5000	-
		[51]	8000				1041 - 2073	-
Linen	Flax	[38]	3979				[1] 995	3739 * 0.25
		[49]					2200	-
		[51]	6000				[1] 1500	6000 * 0.25
		[52]				25%	1566	-
PLA	Corn	[38]	7051				[1] 2641	7051 / 2.67
		[53]			57.2	2.67kg corn /1kg PLA	[1] 2641	7051 / 2.67
		[48]	10630	7440	75.0		[1] 3488	(7440*0.75) / 1.6
		[37]				1.6kg sugar /1kg PLA	4800	
	Sugar beet	[38]	60413				[1] 5236	75735 / (74000/17000) * 0.735/1.6
		[48]	75000	20000	52.0		[1] 6500	17000 * 0.735/1.6
		[37]				1.6kg sugar /1kg PLA	9100	
	Sugarcane	[38]	75735				[1] 7992	60413 / (20000/75000) * 0.52/1.6
		[48]	74000	17000	73.5		[1] 7809	(20000*0.52) / 1.6
		[37]				1.6kg sugar /1kg PLA	8300	-
Lyocell	Spruce	[54]	4020				1471 - 5556	-
		[36]				40%	[1] 1608	4020 / 2.5
	Beech	[54]	4247				1471 - 5556	-
		[36]				40%	[1] 1699	4247 / 2.5

Appendix B Potential production for all yield scenarios

Table B1. Production per EU member state for the three yield scenarios

EU member state	Production in minimum yield scenario (tonnes)	Production in median yield scenario (tonnes)	Production in maximum yield scenario (tonnes)
Poland	235 623	388 070	540 518
Spain	67 083	100 066	133 049
Italy	66 116	100 588	135 060
Portugal	50 688	74 833	98 978
Lithuania	39 752	70 035	100 317
Germany	36 809	62 062	87 314
Greece	31 537	43 104	54 672
France	25 288	44 038	62 788
Denmark	19 245	33 952	48 659
Finland	16 211	25 759	35 306
Czech Republic	16 107	26 884	37 661
Hungary	7 866	13 385	18 904
Sweden	7 442	12 038	16 635
Austria	7 338	12 139	16 940
Croatia	7 264	11 996	16 729
Romania	6 029	10 138	14 246
Netherlands	5 051	8 552	12 053
Slovakia	1 562	2 670	3 778
Latvia	1 028	1 838	2 648
Bulgaria	838	1 432	2 025
Ireland	832	1 456	2 080
Belgium	690	1 210	1 729
Slovenia	629	1 034	1 440
Estonia	551	871	1 191
Cyprus	32	42	52
Malta	0	0	0
Luxembourg	0	0	0
Total production	651614	1048193	1444771