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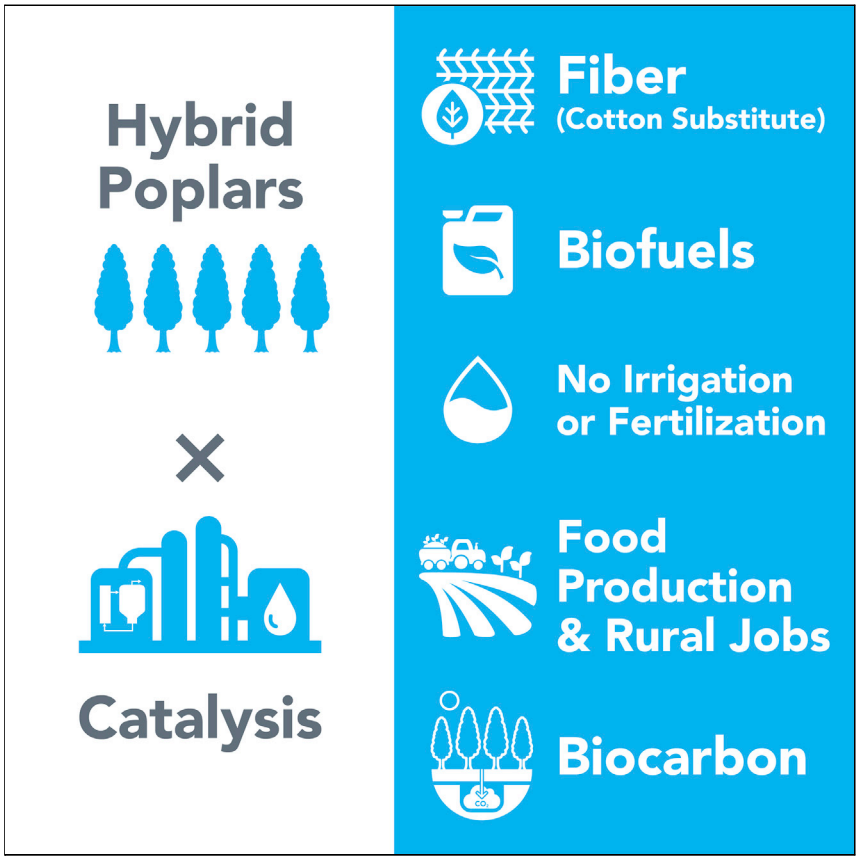

By crossing *Populus trichocarpa* × *P. trichocarpa* from a distant population, hybrid poplar trees were obtained that can grow rapidly on marginal lands in northern climates. These hybrids can be transformed by reductive catalytic fractionation to yield a delignified textile fiber that can be a substitute for cotton as well as a lignin-derived biofuel in the gasoline-aviation-diesel range. The sustainability of this value chain was evaluated by LCA and showed substantial benefits in terms of water use compared with cotton production.

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Highlights

By growing hybrid poplar in northern climates, agricultural lands can be reclaimed

Hybrid poplar grown on marginal lands do not compete with food or forestry

Textiles from poplar would reduce water demand of the resulting fabric considerably

A biofuel in the gasoline, aviation, and diesel range is obtained from lignin

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Lignin-first biorefining of Nordic poplar to produce cellulose fibers could displace cotton production on agricultural lands

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SUMMARY

Here, we show that lignin-first biorefining of poplar can enable the production of dissolving cellulose pulp that can produce regenerated cellulose, which could substitute cotton. These results in turn indicate that agricultural land dedicated to cotton could be reclaimed for food production by extending poplar plantations to produce textile fibers. Based on climate-adapted poplar clones capable of growth on marginal lands in the Nordic region, we estimate an environmentally sustainable annual biomass production of ~11 tonnes/ha. At scale, lignin-first biorefining of this poplar could annually generate 2.4 tonnes/ha of dissolving pulp for textiles and 1.1 m^3 biofuels. Life cycle assessment indicates that, relative to cotton production, this approach could substantially reduce water consumption and identifies certain areas for further improvement. Overall, this work highlights a new value chain to reduce the environmental footprint of textiles, chemicals, and biofuels while enabling land reclamation and water savings from cotton back to food production.

CONTEXT & SCALE

To meet the growing demand of food, materials, chemicals, and energy without crude oil or affecting the climate negatively is a major challenge for this century. By growing an engineered hybrid poplar on non-utilized marginal lands in Nordic climates, highly productive agricultural lands that today are used for cotton production can be reclaimed for food production. This is enabled by the production of wood-based fiber by using an emerging biomass fractionation technology. Besides increasing the capacity to produce food, other advantages comprise a reduced consumption of water and chemicals associated with cotton production. In addition, high yields of a lignin oil that is advantaged for production of biochemicals and biofuels are generated in the fractionation process.

INTRODUCTION

Human population is expected to reach 9–10 billion by 2050.[1] This will lead to an increased demand of food, materials, fuels, and chemicals. In parallel, our primary source of energy and organic materials, crude oil, represents the major source of anthropogenic greenhouse gas (GHG) emissions, catalyzing the urgent need to develop more sustainable value chains. The pressure of a growing population and climate change have concomitantly raised consideration of global food security and sustainability. The issues of water scarcity and food security are particularly acute in arid regions of the world, where currently a considerable area of agricultural land is used for cotton production instead of food.[2]

Cotton farming causes depletion and eutrophication of water resources and brings other negative consequences on local environments through use of pesticides, herbicides, and harvest-aid chemicals.[3] Although organic cotton is often highlighted as an alternative, it still comprises only ~1% of global cotton production.[4] Today, cotton fields cover 34.5 million (M) hectares (ha) of arable land worldwide with an average yield of 2.14 tonnes ha^{-1} $year^{-1}$ seed cotton,[5] corresponding to a global average annual production of cotton lint of 0.76 tonnes ha^{-1}.[3] The industry of such scale consumes on average 2,955 m^3 of irrigation water (blue water) and produces 996 m^3 of wastewater (gray water) per ton of produced cotton lint.[6,7]

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As an alternative to cotton fibers, we hypothesize that cotton fibers could be replaced with regenerated cellulose fibers from trees grown on marginal lands in the northern temperate and boreal climates. Regenerated cellulose, under trade names such as lyocell, tencel, modal, and viscose can replace cotton in fabrics to a great extent.[8,9] If this were the case, large land areas could be made available for food and feed production in arid regions of the world, with the potential to mitigate the negative environmental impacts related to cotton production. Environmentally sustainable production of raw material for cellulose textile fiber is brought about by mixing poplar wood from short rotation forestry (SRF) with birch (*Betula pendula*) and beech (*Fagus sylvatica*) wood.[10] The term SRF refers to plantations of fast-growing *Populus* spp. trees grown for 5–25 years[11,12] with significant capacity for carbon sequestration and no need for irrigation or fertilization. An advantage of SRF systems is that they can achieve high productivity on unutilized, marginal lands that are not economically viable in agriculture.[13] Recent estimates suggest that 43 M ha of marginal land in Europe is unutilized that potentially could be used for poplar tree farming.[13] In addition to wood production, *Populus* plantations provide other ecosystem services in terms of enhanced biodiversity,[14] the ability to utilize transiently high amounts of water for growth in a changing climate with extreme rainfalls, and in the accumulation of nutrients leached from adjacent agricultural soils.[15,16] This multifunctionality makes SRF with *Populus* an important tool to increase ecosystem resilience and contributes to the actions for climate neutrality proposed by the European Green Deal.[17–19]

Conversion of lignocellulose to textile fiber requires pulping. Traditional, kraft pulping valorizes mainly the cellulose fraction, which is around 50% of woody biomass,[20] whereas the lignin and hemicellulose fractions are burned for heat and power. Alternative technologies for the upgrading these two biomass components have been intensively studied in the last decades. In particular, the "lignin-first" approach employs active stabilization of the lignin fraction during pulping to avoid undesired repolymerization of lignin fragments.[21–26] The most common lignin-first biorefining approach is reductive catalytic fractionation (RCF), in which heterogeneous metal catalysts are added to the biomass before treatment with solvent to depolymerize lignin and stabilize the reactive lignin fragments *in situ*.[22,23,27–29] The main focus of these studies is to generate high yields of monophenolic compounds from the lignin, and the polysaccharides fraction has mostly been analyzed or hydrolyzed to glucose and xylose.[30,31]

Here, we present an approach that ultimately could reclaim agricultural land currently used to produce cotton for food production via use of RCF as a pulping technology to make textile fiber and lignin-derived biofuels. This approach uses novel poplar clones, developed by classical breeding, that are adapted for the Nordic climate and can grow on marginal lands, thus not competing with either forestry or agriculture. With life cycle assessment (LCA), we estimate that textile fiber production from poplar via RCF can achieve similar cumulative energy demand (CED) and global warming potential (GWP) to cotton production but with an order of magnitude reduction in water usage.

RESULTS

The proposed poplar-to-viscose fibers value chain consists of poplar cultivation in the Nordic region, RCF to produce brown pulp and lignin bio-oil from poplar, downstream processing of the brown pulp into dissolving grade pulp, and production of viscose fibers from the dissolving grade pulp (Figure 1). In this section, we present

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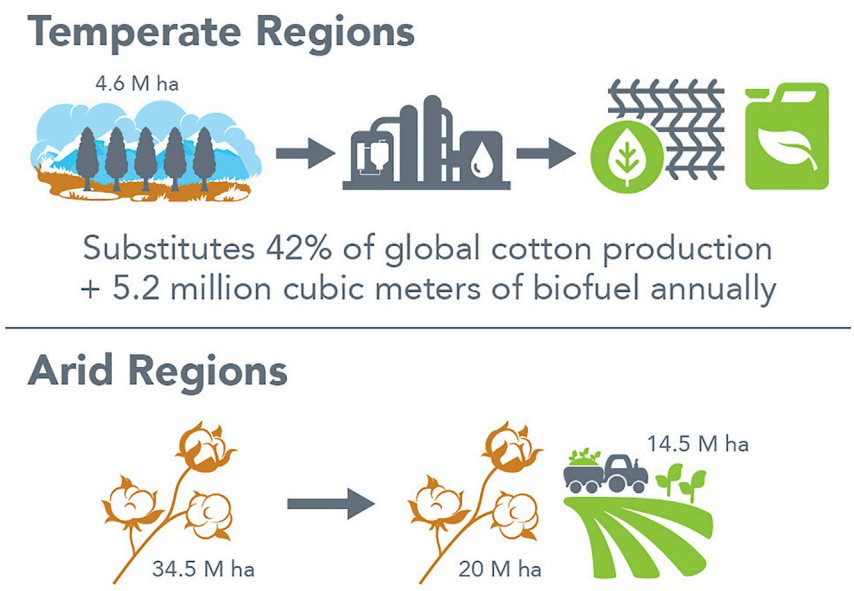

Figure 1. The concept of using marginal land in northern Europe to produce lignocellulose for textile fiber while substituting cotton and reclaiming arable land for food production worldwide in the regions with more arid climate

Replacing a portion of cotton fiber with cellulose fiber from north European poplar plantation has the potential to free up 14.5 M ha of fertile agricultural land currently used for cotton production.

results for each stage in the value chain including expected poplar biomass yields, RCF biorefinery details, and a cradle-to-gate LCA comparing poplar viscose fibers with standard viscose and with cotton fibers (Figure S1).

Climate-adapted clones extend the area of high biomass yield to the temperate and boreal regions at higher latitudes

In this study, we present the yields of poplar clones bred for relatively cold northern European climates on marginal land. Poplar cultivation has received considerable attention worldwide due to its high biomass production potential in temperate climate zones.[32–34] At higher latitudes in northern Europe, the area of poplar plantations has been limited by the availability of climate-adapted poplar clones. Poplars have only been planted on set-aside and marginal land in Southern Sweden since the beginning of 1990s and today occupy an area of 2,430 ha.[35] Marginal land in the current study includes low-yield set-aside arable land, the fields characterized by low accessibility or patchiness that do not allow for an effective utilization of agricultural machinery and implements, as well as overgrown land not yet categorized as forestland (supplemental information and Table S1). A large portion of such land area is on relatively unproductive organic or sandy soils managed as hayfields under the EU subsidiary system, where the subsidy represents the only actual revenue for the landowner and no value in terms of raw material supply (*vide infra*).

The production potential of this system is estimated by the growth data of mainly two clones with complementary climate adaptation and geographic deployment range.[36,37] An existing commercial poplar hybrid "OP42" (*Populus maximowiczii* × *trichocarpa*) achieves high biomass production in Denmark, northern Poland, and Southern Sweden and is an established clone on the market.[38–40] A new group of clones have been bred by Swedish University of Agricultural Sciences, representing novel intraspecific hybrids within the species *P. trichocarpa*,

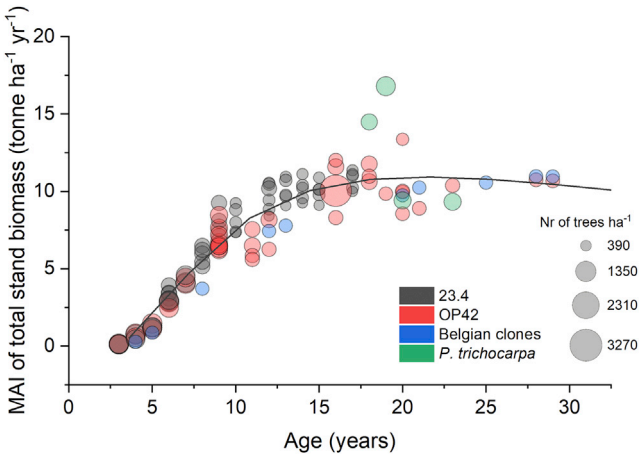

Figure 2. Mean annual biomass increment (MAI) of poplar stands measured in Sweden and Lithuania

The size of circles corresponds to the number of trees per hectare. The plots of clone "23.4" grown at 60°N–61°N in central Sweden have shown the same yield potential as clone "OP42" in Southern Sweden.

adapted to climates at higher latitudes in northern Europe (up to 61°N) where they can achieve equally high yields as clone "OP42" on lower latitudes (Figure 2).[41] Clone "23.4" in the current study represents this group. We recorded yield data at 4 different locations for clone "23.4" and at 12 different locations for clone "OP42" in Swedish and Lithuanian experimental and commercial plantations. The northernmost plantation for clone "23.4" is located at 61°18′N and was 8 years old in the beginning of 2021 (site 16 in Table S2). The oldest plantation with intraspecific hybrids for northern Europe including clone "23.4" is 17 years old (site 1 in Table S2).

Biomass production estimates

Stand density data were combined with allometric relationships, wood density data, and diameter/height relationships from earlier studies[36,42,43] to obtain stem volumes, stem diameters, and dry weights over time of harvested poplars. The growth of total stand biomass (Y) over time was fitted using the growth function:

$$Y = a_1 e^{(-a_2 A^{-a_3})} \quad \text{(Equation 1)}$$

where A is the stand age at the time of measurement and $a_1 = 638.69$, $a_2 = 20.518$, and $a_3 = 0.985$ are estimated function parameters. The stand biomass over time is presented in Figure 2 as the mean annual increment (MAI) obtained by dividing the total stand biomass from the fitted function by the stand age, A. Thus, the maximum MAI of measured poplar stands reached 10.9 tonnes ha^{-1} year^{-1} by the age of 21 years. The MAI used to develop the life cycle inventory (LCI) for poplar farming was 11% lower, i.e., 9.7 tonnes ha^{-1} year^{-1} to correct for losses of biomass expected to occur during the harvesting operations.[44]

Details of biomass yields are provided in Table S3 and biomass composition in Table S4. The anticipated MAI of 9.7 tonnes ha^{-1} year^{-1} total biomass corresponds to 6 tonnes ha^{-1} year^{-1} (268.6 tonnes ha^{-1}) pulpwood that can be harvested and utilized. An additional 2.5 tonnes ha^{-1} year^{-1} (110.6 tonnes ha^{-1}) forest residues and 1.1 tonnes ha^{-1} year^{-1} (47.4 tonnes ha^{-1}) bark are produced and used as a source of energy. Forest residues from thinning operations (10.4 tonnes ha^{-1}) are not utilized but left in the plantation to secure nutrition and soil carbon balance.

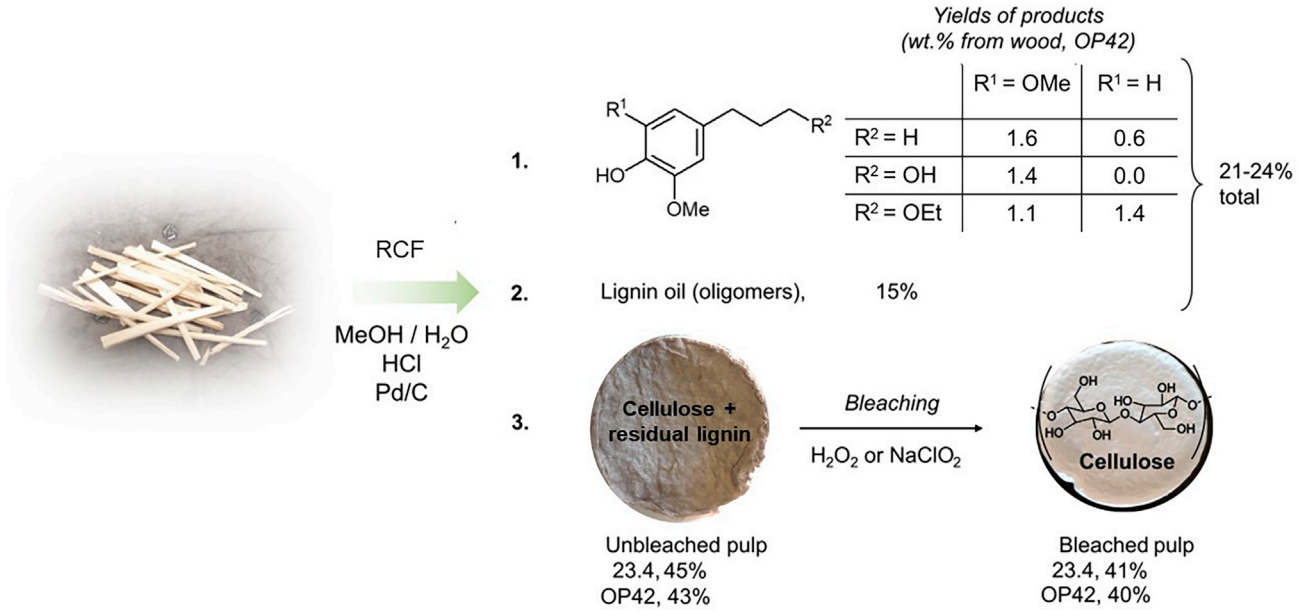

Figure 3. Catalytic fractionation of poplar wood to yield cellulose-based pulp and bio-oil

Reductive catalytic fractionation of poplar to dissolving pulp and bio-oil

To evaluate the possibility to produce dissolving grade pulp from poplar clones and also to generate a lignin oil, a "lignin-first" approach was pursued.[25,45] These methodologies have not been reported for the production of dissolving grade pulp. To generate a high-quality pulp, RCF was performed in EtOH-H_2O 65:35 v/v in the presence of hydrochloric acid and caged Pd/C in catalytic amounts (2.5 wt %) (Figures S4 and S6).[46,47] The poplar clones contained rather low quantities of hemicellulose (12%–15%; Table S4), and instead of isolating this fraction, the hemicellulose was used as an internal hydrogen donor for the reductive stabilization of the lignin fraction and ended up in the bio-oil.[48,49] Wood chips from both clones OP42 and 23.4 were evaluated for RCF (Figure S3). It was found that running the RCF reaction without stirring for 3 h at 175°C gave the optimal results in terms of pulped wood and a bio-oil (Figure 3). The pulped wood was easily disintegrated (Figure S5) by mechanical force to produce a brown fluffy pulp at 43 and 45 wt % yield ("OP42" and "23.4," respectively) containing 3% lignin. Sodium chlorite was used to bleach the generated pulp in 40% and 41% yield with high intrinsic viscosity (1,005 and 985 mL/g) for clones OP42 and 23.4, respectively. Chemical analysis[50,51] showed a dissolving grade pulp with a high α-cellulose content (>94%) and brightness (International Organization for Standardization [ISO] brightness 90%) (Figure 4; Figures S7 and S8; Tables 1 and S19).

Bio-oil upgrading

The mixed bio-oil from both clones was evaluated for chemicals and biofuel production. The monophenolic compounds could be distilled off to yield 10 wt % of the initial wood mass. This corresponds to around 40% of the lignin and is considered a theoretical maximum yield of 85%, based on the β-O-4 bond content in the native lignin determined by thioacidolysis. This fraction could be used to produce fine chemicals.

The oligomeric fraction of lignin requires further processing. As this fraction both contains recalcitrant C–C bonds and has a high oxygen content,

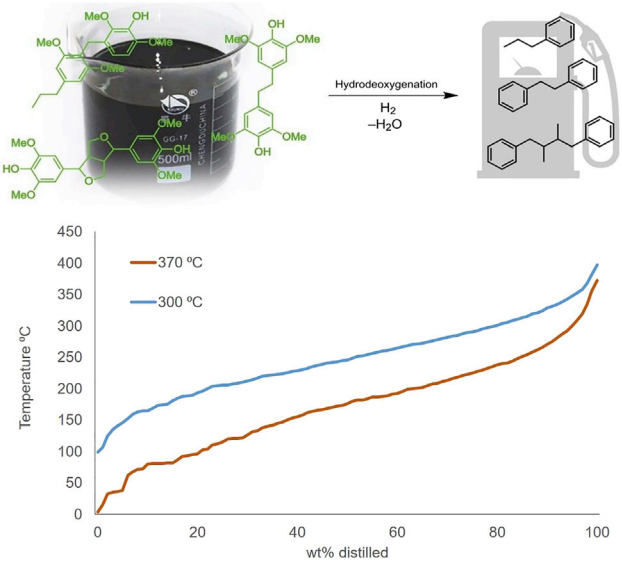

Figure 4. Hydrodeoxygenation of oligomeric fraction yields hydrocarbons in fuel range
Simulated distillation curves of biofuel obtained at different HDO reaction temperatures.

hydrodeoxygenation (HDO) was performed (Figure S9). For demonstration purposes, we transformed the whole lignin fraction without distilling of the monophenolics. During hydroprocessing, both cracking of C–C bonds and HDO, i.e., cleavage of C–O bonds, occur to produce hydrocarbons (Figure 4). The reaction was carried out at 300°C or 370°C under 50 bar of H_2 using a Pt/MoO_3 catalyst on a titania support.[52–54] Although the carbon yield is high, above 90% at both reaction temperatures, the weight yield is low due to HDO reactions that reduce the weight by 40% and is 15 wt % of the initial wood. The hydrocarbon lignin oil was characterized by means of simulated distillation for evaluation as a biofuel. Depending on temperature of the hydrotreatment, content of the hydrocarbons within gasoline (<200°C, 20%–60%), diesel (200°C–350°C 30%–60%), and aviation (150°C–280°C) ranges could be obtained (Figure 4; Tables S19 and S20).[55,56]

Life cycle assessment and techno-economic analysis

A cradle-to-gate LCA was performed to assess key environmental impacts of the proposed poplar-to-viscose value chain and enable comparison to existing fibers that will potentially be displaced by poplar-derived viscose fibers (Figure S1). The LCA system boundary comprised the cultivation, harvest, and transport of woody raw materials from poplar SRF, conversion of poplar biomass to brown pulp and lignin-based bio-oil (Tables S3, S5, S6, and S18) via RCF, processing of brown pulp into dissolving grade pulp, and the production of viscose fibers. As separate analyses, direct land use change carbon impacts of poplar SRF and the environmental impacts of the biopower produced from poplar tops and branches were also quantified. A detailed description of the LCA goal, scope, calculations, and assumptions can be found in the supplemental information, sections "life cycle assessment," "material and energy inputs to poplar farming, shipping and preprocessing," and "material and energy inputs to RCF biorefinery." Calculations for estimating direct land use change carbon impacts can also be found in the supplemental information section "life cycle assessment."

GWP, CED, and the available water remaining (AWARE) indicator are the environmental impacts quantified for poplar viscose fibers (Tables S7–S14). The AWARE

Table 1. Dissolving grade pulp parameters for a production of generated cellulose

Parameter	Unit	Unbleached OP42	Bleached OP42	Unbleached 23.4	Bleached 23.4
Brightness	% ISO	–	90	–	90
Intrinsic viscosity	mL/g	–	1,005	–	985
Degree of polymerization	C_6 unit	–	1,511	–	1,478
Klason lignin	%	2.8	n/a	3.1	n/a
α-Cellulose	%	–	94.5	–	94.3
Glucan content	%	90	100	94	95
Ash content	%	0.4	0.04	0.25	0.05

The RCF reactions were run in parallel reactors loaded with 0.8 g wood chips and 10 mL of ethanol-water 65:35 (v/v) together with Pd/C (80 mg) at 175°C for 3 h. The pulp was separated by filtration, disintegrated, and bleached using $NaClO_2$ to produce the dissolving grade pulp.

indicator is not a direct measure of water use within a value chain; it provides an estimate of the likelihood that a water user (human or ecosystem) within the same watershed will be deprived of water.[57] A higher AWARE indicator value indicates a greater likelihood of water deprivation. The same impacts were calculated for two additional fibers, viscose fibers produced from current feedstocks and production technology and cotton fibers produced from current farming practices and production technology, as points of comparison.

The inventory of material and energy inputs to the poplar SRF production system are calculated according to the practices in conventional Nordic forestry (see details in supplemental information, section "material and energy inputs to poplar farming, shipping and preprocessing"). The average transport distance for pulpwood timber is set to 100 km. Material and energy inputs to the RCF biorefinery are calculated based on an Aspen model and techno-economic analysis (TEA) (see details in supplemental information, section "material and energy inputs to RCF biorefinery").[58] Based on the efficiency of catalytic fractionation, each hectare of the modeled poplar SRF can yield 216 tonnes viscose fibers over the 45-year period (4.8 tonnes viscose fibers $year^{-1}$). In addition to viscose fibers, this value chain co-produces tops and branches suitable for biopower generation (2.0 MWh electricity $year^{-1}$), excess electricity from the RCF biorefinery (266 GWh $year^{-1}$), and lignin bio-oil (314,834 tonnes $year^{-1}$).

Figure 5 compares total life cycle impacts for the three fibers, with GWP for RCF viscose shown for several levels of carbon uptake by growing (aboveground) poplar biomass. Results are shown for production in Sweden; the same set of results for production in Europe is provided in the supplemental information. The RCF viscose value chain offers modest savings in GWP and CED over cotton and current viscose technology through Kraft pulping. At the default carbon uptake level (1.87 kg CO_2 dry kg aboveground $biomass^{-1}$), RCF viscose produced in Sweden has 11% lower GWP than current technology viscose and 2.4% lower GWP than cotton. The GWP savings is due largely to the carbon uptake during poplar cultivation and partially to the emissions credits from the sale of excess electricity by the RCF biorefinery.

The poplar SRF used in the RCF viscose value chain uses minimal herbicides, no fertilizers, and no irrigation, in contrast to standard cotton farming which intensively uses all three farming inputs. This difference in farming practices leads to the substantially lower AWARE indicator for RCF viscose compared with cotton (94% lower than cotton) and keeps RCF viscose comparable with current viscose technology (1% higher). Displacing conventional cotton fibers with RCF-derived viscose would therefore free up a substantial amount of water for other users in the same watershed, although the location of the additional available water would depend on where cotton farming is displaced.

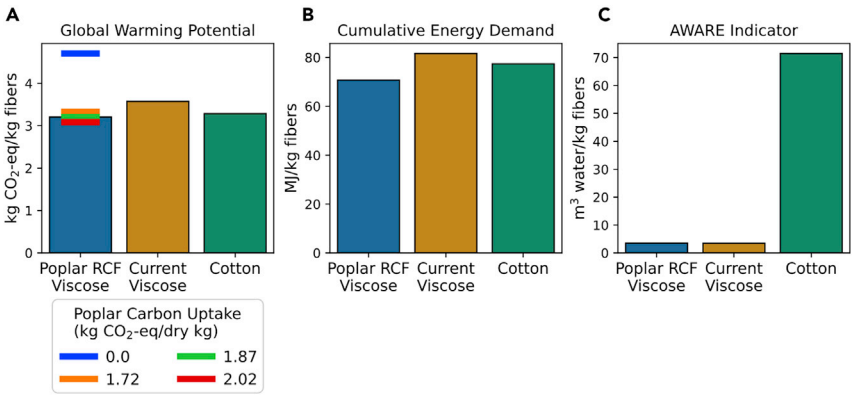

Figure 5. Life cycle impact comparison between poplar RCF viscose produced in Sweden, current technology viscose through Kraft pulping, and current technology cotton

(A) GWP for the three fibers; poplar RCF viscose (blue bar) offers modest reductions in GWP over current viscose and cotton fibers, although the magnitude of reduction depends on the level of carbon uptake due to poplar cultivation.

(B) CED; poplar RCF viscose again offers modest reductions in CED compared with the two other fibers.

(C) AWARE indicator values; both poplar RCF viscose and current technology viscose offer a full order of magnitude reduction in the AWARE indicator compared with cotton fibers.

Figure 6 shows poplar viscose life cycle impacts disaggregated by value chain process. Each bar indicates impacts produced directly by the value chain process as well as upstream during production and transportation of material and energy inputs to the process. This form of disaggregation can enable the identification of environmental hot spots in the value chain: processes that contribute an inordinate amount to the total environmental impact and can potentially be improved through future research efforts. Across all three environmental impacts, the viscose production process contributed more impacts than any other process. The carbon offsets from poplar cultivation are substantial relative to the GWP of the rest of the value chain. Similarly, CED of RCF viscose is lower than that of current viscose (14% lower in Sweden) and of cotton (9.8% lower in Sweden). Viscose life cycle impacts attributed to the RCF biorefinery are shown in Figure S2 disaggregated by biorefinery input.

To provide a more complete picture of the environmental and climate implications of this value chain, impacts from the use of tops and branches for biopower and the carbon impacts of direct land use change were calculated and are presented separately from the LCA study. In total, 109 dry tonnes ha^{-1} of tops and branches are produced during the 45-year period. This biomass is assumed to be used for biopower generation, with an average transport distance to the biopower plant of 50 km. Environmental impacts and total biopower generation are calculated based on a combined heat and power process using a 6,667-kW turbine,[59] adapted to include carbon uptake by feedstock cultivation. Therefore, 91.8 MWh of electricity can be generated from poplar tops and branches during the 45-year period. GWP, CED, and AWARE indicator values per kWh of biopower electricity from poplar tops and branches and the default wood chip blend are shown in Table 2.

Biopower from poplar tops and branches results in higher GWP and AWARE indicator per kWh but exhibit a substantially lower CED per kWh. Wood chips used in the default biopower process are from hardwood and softwood forestry management, such that there are no inputs for establishment (site preparation, seedling growth, or planting) or management (weed control or trimming). These wood chips therefore

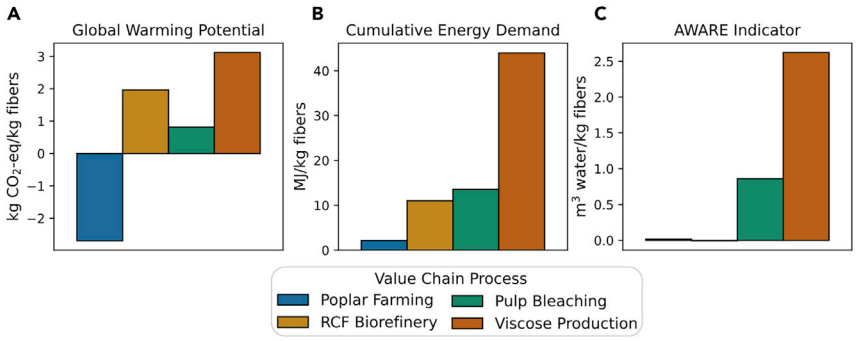

Figure 6. Life cycle impacts by the value chain process for poplar viscose fibers

(A) Global warming potential with the default level of carbon uptake (1.87 kg CO_2 kg dry biomass^{-1}) and with the RCF biorefinery located in Sweden.

(B and C) CED (B) and the AWARE indicator (C). Across all three impacts, viscose production contributes more to the total impact than any other process.

are produced from only inputs to harvesting operations, which in this case means they are less material and energy intensive to produce than tops and branches from the poplar farming practices of this work.

To calculate the direct carbon impacts of converting marginal land to the poplar SRF of this work, we apply the IPCC guidelines[60,61] on calculating carbon impacts for grassland converted to forest land. We perform the calculations on a per-hectare basis and assume that the poplar farming practices proposed in this work are being applied to land that has not been cultivated for a couple of decades in Sweden. Forest land is chosen as the end state of the land because the assumptions applied to standard perennial crops in the IPCC guidelines are not well aligned with the poplar farming practices proposed in this work, due to the low management intensity and the relatively long rotation time of the poplar plantation. The complete calculations, including intermediate values and sources for all data, are given in the supplemental information, section "impact assessment and sensitivity analysis" (Tables S15–S17).

The total amount of carbon removed from the atmosphere by two poplar rotations during the 45-year period, including carbon stock changes in aboveground and belowground biomass, in dead organic matter, and in mineral soil, is estimated to be between 282 and 456 tonnes C ha^{-1}. The annual change in carbon stock is estimated to be between 6 and 12 tonnes C ha^{-1} year^{-1} for the first 20 years of this period and between 6–9 tonnes C ha^{-1} year^{-1} for the remaining 25 years. These calculations are based on the time it takes for the carbon stock changes to reach steady state, which is not the same as the poplar rotation time. Of this carbon stock, approximately 58–67 tonnes C ha^{-1} is released back into the atmosphere in the short term, from tops and branches combustion to generate biopower. The fate of the carbon in RCF poplar viscose and in lignin bio-oil is uncertain, as downstream processing steps and disposal practices outside the scope of this work will determine how much of this carbon is released back into the atmosphere and over what time frame.

DISCUSSION

The aim of this work is to estimate the potential to free up useful agricultural land, currently used for cotton production, for food production by substituting cotton with dissolving cellulose from poplar trees grown on marginal land in northern temperate and boreal climates.

Table 2. Environmental impact summary of biopower produced from poplar tops and branches and the default wood chips produced from various forestry methods

	Poplar tops and branches	Wood chips
GWP (kg CO_2 equiv kWh^{-1})	n/a	n/a
No carbon uptake	1.62	1.58
Default carbon uptake (1.87 kg CO_2 kg dry $biomass^{-1}$)	0.0448	0.00746
CED (MJ kWh^{-1})	1.27	17.47
AWARE (m^3 water kWh^{-1})	0.0121	0.00725

The growth potential of poplar plantations was estimated from the data collected for clones "OP42" and "23.4" in Sweden and Lithuania, where the latter clone enables northward extension of commercial poplar plantations up to at least 61°N latitude with maintained high biomass yields. The estimates of marginal land in a defined temperate area located between 7°E and 36°E longitudes, and 53°N and 62°N latitudes, were based on the available data for Sweden and Lithuania, located within this geographical region. Our calculations revealed that 2.9% of land area, on average, is available for alternative use in the Baltic Sea region, which corresponds to 4.6 M ha. We consider the suggested marginal land in our defined region as a lower limit, whereas a significantly greater potential has been proposed, e.g., by Kluts et al.[62] It should be noted that similar areas are also available in both North America and east of 36°E longitude in Europe. In Europe alone, there is an estimate of 22.4 M ha of arable land that is not utilized for food production.[13]

On the 4.6 M ha of marginal areas defined in this study, an annual biomass growth of 44.6 M tonnes poplar wood is estimated based on the collected data, with 27.6 M tonnes being harvested as pulpwood. This raw material can be converted to 11.0 M tonnes dissolving grade pulp via the RCF technology followed by bleaching. In addition to the generated pulp, this value chain produces 5.2 million m^3 of biofuel (lignin oil ~180 M GJ) and 13.6 M tonnes of dry forest residues (tops, branches, and bark) annually with the heating value of 302 M GJ. In contrast to cotton production, no irrigation or fertilization is required in the production of poplar wood. The production levels of short rotation forests with poplars used in current study, i.e., 10.9 tonnes of total aboveground leafless biomass per hectare and year, are in the range reported in earlier analysis of poplar and willow SRF systems in Sweden.[32,44,63–67]

In this study, we considered marginal land as grassland when calculating changes in carbon stocks due to changed land use. The production of textile fibers from poplar wood would have even smaller GWP compared with planting trees on marginal land, if the alleys of poplars were established on the fields with annual crops. This is because initial carbon stocks in cropland soil are significantly smaller compared with carbon stocks in grassland.[68] Moreover, fast-growing deciduous species, such as poplars, provide other ecosystem services in addition to woody biomass production. Poplars as alleys or buffer zones strategically placed between fields with annual crops and ditches, rivers, lakes in agricultural landscapes would significantly reduce flow of nutrients leaching to watercourses.[16] Further advantages with fast-growing trees comprise reduced N_2O emissions to atmosphere;[69,70] reduced soil erosion caused by surface water runoff,[71] tillage, or wind;[72] reduced carbon loss from agricultural soils;[73] and increased biodiversity.[74,75]

Currently, 34.5 M ha fertile agricultural land is used to produce the annual demand of 26.2 M tonnes cotton fiber. This production requires 77 billion tonnes of blue water as well as large amounts of chemicals. The desertification of Aral Sea, the world's fourth largest lake, within a few decades of irrigation of the regions cotton fields

provides a striking illustration of the negative environmental impact of cotton production. Thus, replacing a portion of cotton fiber with cellulose fiber from north European poplar plantation has the potential to free up 14.5 M ha of fertile agricultural land currently used for cotton production while saving 33 billion tonnes of blue water. This was confirmed in the LCA, where the major benefit of applying the proposed route is savings in water. Using the "lignin-first" approach described, an additional 5.2 M m^3 of biofuel would be generated.

Herein, we introduce a proposed value chain to produce a cotton substitute on marginal lands that are currently not used either in agriculture or in forestry. By expanding short rotation forests with climate-adapted poplars with a net biomass growth of 10.9 dry ton weight ha^{-1} $year^{-1}$ to northern climate zones, it is possible to convert large areas of highly productive agricultural land currently used for cotton production to food and feed crops. A novel methodology, RCF, has been introduced for the first time to yield a pulp that meets the criteria for wood-based textiles. The methodology has the advantage of producing a lignin-derived bio-oil that can either be used for production of chemicals such as benzene, toluene, and xylene (BTX) or biofuels in the gasoline-aviation-diesel range. The energy balance of the whole value chain has been evaluated where in addition to 2.4 t of textile pulp a net surplus energy of 63.6 GJ per ha^{-1} $year^{-1}$ is generated. Of this surplus energy, 40 GJ ha^{-1} $year^{-1}$ is lignin oil and the rest forest residues and bark. The entire value chain needs 4.3 GJ ha^{-1} $year^{-1}$ for cultivation and transport of this woody raw material to factory gate and 43 GJ ha^{-1} $year^{-1}$ for industrial processing.

By employing this value chain in a well-defined region in northern Europe (7°E–36°E; 53°N–61°N degrees) that is not utilized for either annual crops or forestry, a production of 11.0 M tonnes of dissolving grade pulp and 5.2 M m^3 of biofuel has been estimated. Implementing this technology would thus have the potential to free up 42% of all the area that currently is used for production of cotton. Other advantages comprise less usage of chemicals and water for the production of textile fiber, and the ability to fixate atmospheric carbon dioxide.

EXPERIMENTAL PROCEDURES

Resource availability

Lead contact

Further information and requests for resources regarding cultivation of SRF should be directed to and will be fulfilled by the lead contact, Anneli Adler (anneli.adler@slu.se); for RCF and upgrading of pulp and lignin oil further information and requests should be directed to and will be fulfilled by the lead contact Joseph Samec (joseph.samec@su.se); for LCA, further information and requests should be directed to Gregg T. Beckham (gregg.beckham@nrel.gov).

Materials availability

Samples of clones 23.4 and OP42 are available in small quantities from Anneli Adler.

Data and code availability

This study did not generate any datasets.

SUPPLEMENTAL INFORMATION

Supplemental information can be found online at https://doi.org/10.1016/j.joule.2022.06.021.

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AUTHOR CONTRIBUTIONS

A.A. conceived the research idea, was responsible for the cultivation of SRF, and contributed to writing the article. I.K. performed the RCF and HDO experiments and contributed to writing the article. A.K. performed calculations on biomass yields and mass balances and contributed to writing the article. K.R.B. performed all upgrading of the cellulose to dissolving pulp and contributed to writing the article. R.J.H. performed all LCA studies. E.S. contributed to chemical analysis of wood. A.W.B. performed modeling of the RCF process used in the LCA studies. A.J.H.-A. contributed to the optimization of RCF on sawdust. A.M. contributed RCF on sawdust and writing the article. H.H. contributed with analysis of dissolving grade pulp. A.P.M. contributed to disintegration of pulp and bleaching of pulp. G.T.B. contributed to the discourse and writing the article. J.S.M.S. conceived the research idea and is responsible for RCF and downstream processing and contributed to writing the article.

DECLARATION OF INTERESTS

J.S.M.S. is professor at SU and cofounder of RenFuel, which is a company that have IPR on RCF technology.

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