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Environmental Footprints of Cotton and Cotton Fibres

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Content

1 Background and Objective

1.1 Background

The environmental impacts of the textile industry have been increasingly discussed in recent years. Cotton, as one of the most widely used fibres in the production of clothing and home textiles, plays a significant role in the environmental impact of textile production. In addition to the CO_2 footprint, the water, land, and phosphate footprints are of particular importance. A related question of interest is whether organic cotton has a lower environmental impact than conventional cotton.

Environmental footprints of cotton and cotton fibres vary substantially in the literature, which is why their use in life cycle assessments (LCA) to evaluate textiles is limited. For example, CO_2 footprints of cotton fibres range from 1.3 kg CO_2 eq./kg [Cotton Inc. 2017] to 4.1 kg CO_2 eq./kg [Ecoinvent 2020].

This is due to the fact that analyses are sometimes based on inconsistent assessment approaches, varying system boundaries, an inadequate data basis, or different methodological approaches. For example, the values for organic cotton fibres in the Ecoinvent LCA database are based on only a single cotton plantation in India [Ecoinvent 2020]. Another example is the otherwise comprehensive LCA provided by Cotton Inc., which does not take into account the scarcity of water in the respective countries of origin when calculating the water demand [Cotton Inc. 2017].

1.2 Objective

The aim of this study is to derive the most important environmental footprints for cotton and cotton fibres produced worldwide, based on consistent and up-to-date assessment methods.

In addition to the CO_2 footprint, which is important from a climate protection perspective, other environmental impact categories, such as the water, land and phosphate footprints will be considered. The reasoning is that these finite resources are largely used for the agricultural production of renewable resources. In addition, there are already major conflicts over these resources today, so that in our view they should be taken into account in an environmental assessment of renewable resources in the future.

The water and land footprints will not only quantitatively account for the resources used, but also be evaluated according to the degree of their environmental impact on the basis of scarcity (water) or their degree of "naturalness" (land).

In order for the results to be used consistently for all cotton products, the following products will be considered: conventionally and organically produced seed cotton as an intermediate product for the production of cotton fibres, as well as conventionally and organically produced cotton fibres. For these, environmental footprints will be quantified separately. Furthermore, the data underlying the environmental footprints will be reported for the following by-products: cotton seeds, gin trash, cottonseed oil, cottonseed meal, cottonseed hulls, and cotton linters.

2 Methodology

2.1 Products and Environmental Footprints Considered

2.1.1 Products Considered

As described in chapter 1.2 the environmental footprints of conventionally and organically produced seed cotton as an intermediate product for the production of cotton fibres as well as conventionally and organically produced cotton fibres will be calculated and reported. Furthermore, following by-products will be considered: cotton seed, gin trash, cotton seed oil, cottonseed meal, cotton seed hulls and cotton linters.

2.1.2 Environmental Footprints Considered

The methods used to calculate the individual footprints are described below.

CO_2 footprint:

- The CO_2 footprint was calculated in accordance with ISO 14046 [ISO 2018]. It includes all greenhouse gas emissions (including carbon dioxide CO_2, methane CH_4, nitrous oxide N_2O) converted to CO_2 equivalents. The conversion factors according to [IPCC 2021] were used to achieve comparability.
- The greenhouse gas emissions associated with land use and land use change were taken into account using the attributional land use/land use change (aLULUC) approach [Fehrenbach et al. 2020].

Water footprint:

- As clean (drinking) water is a scarce resource in some regions of the world and agricultural production uses increasing water resources, the water footprint plays an increasingly important role in the environmental assessment of renewable resources. In the form of “virtual” water, (imported) products leave a water footprint, which is influenced by agricultural production, processing and water availability in a region.
- The calculation of the water footprint is based on the Available WAter REmaining (AWARE) method [Boulay et al. 2018] and takes into account the water availability in a country in relation to the global average apart from the amount of water required for production. The methodology was extended to include irrigation technology and water desalination (combined AWARE, irrigation technology efficiency and desalination factor, ifeu-internal data). The water footprint is given in m^3 water equivalents.

Land footprint:

- Due to the increasing use of agricultural land for non-food purposes, there is increased land use competition between the cultivation of food and fodder crops, plants for material use or fuel production, and nature conservation areas (Food, Feed, Fibre, Fuel, Flower debate).
- The calculation is based on the hemeroby concept, in which the agricultural area used for the production of a product is converted into equivalents of one year of fully sealed area. This is done by assessing the distance of the production area to almost natural areas ("distance to nature") [Fehrenbach et al. 2019]. The resulting unit is square metre years of natural area occupancy (also called *Distance-to-Nature-Potential*, DNP).

Phosphate footprint:

- Due to the finite nature of phosphate rock deposits, the amount of phosphate "consumed" by a product has to be considered. This is particularly relevant for the use of phosphate fertilisers in food production.
- The amount of phosphate per kg of product is calculated in g phosphate rock equivalents. For details see Reinhardt et al [2019].

2.2 System Boundaries of the Products

Cotton (*Gossypium*) is one of the oldest tropical cultivated plants for obtaining fibres. Of the more than 20 species, 4 species are cultivated (*Gossypium herbaceum, G. hirsutum, G. barbadense*, and *G. arboreum*). Cotton plants are perennials, but are cultivated as annuals. During the ripening period of the capsule ("cotton boll") seed hairs grow, which, together with the seeds, can be harvested after the capsule has burst open [Lieberei et al. 2012].

Depending on the growing region, harvesting takes place manually or using picking machines (mainly in the USA and Russia). After harvesting, seed cotton is transported to factories (gins) where the cotton fibres are separated from the seeds by ginning machines. The gin trash produced during the cotton ginning process is used as fuel for energy production. The cotton fibres can then be spun into cotton yarns for textile production, while oil mills extract cottonseed oil and meal from the cottonseeds. The seeds are first freed from fine hairs, the cotton linters, then hulled and the resulting kernels pressed into oil and press cake. Cotton linter is typically used in the paper and cellulose industry because of its high cellulose content of over 80%. The cottonseed hulls are used as fibre-rich feed for ruminants, but can also be used as a substrate for mushroom cultivation or for various industrial purposes [Heuzé et al. 2015]. Cottonseed oil, which is toxic in its raw state, is largely processed into edible oil through purification and bleaching steps and is used, among other things, for deep-frying, as salad oil or for the production of margarine [Lieberei et al. 2012]. The residual oil content is extracted from the press cake using solvents. The remaining cottonseed meal serves as a valuable animal feed due to its high protein content.

The system boundaries are set as follows:

Seed cotton:

- Agricultural cultivation including all upstream processes such as fertiliser and fuel production as well as transport

Cotton fibres:

- See seed cotton
- Logistics and ginning of seed cotton into marketable cotton fibres

Cotton seeds:

- See seed cotton
- Logistics and ginning of seed cotton into cotton seed

Gin trash:

- See seed cotton
- Logistics and ginning of the seed cotton to gin trash

Cottonseed oil, crude:

- See cotton seeds
- Logistics as well as hulling and pressing of the cotton seeds/extracting the oil from the press cake to cotton seed oil.

Cottonseed meal:

- See cotton seeds
- Logistics as well as hulling and pressing of the cotton seeds/degreasing of the press cake into cottonseed meal

Cottonseed hulls:

- See cotton seeds
- Logistics and hulling of cotton seeds into hulled seeds and hulls

Cotton linters:

- See cotton seeds
- Logistics and removal of the cotton linters from the cotton seed

Cottonseed oil:

- See crude cottonseed oil
- Logistics and refining of the crude oil into edible oil

Credits from by-products are calculated by assessing substituted (reference) products and their upstream chains (see Figure 1 on the following page).

2.3 Definitions of Cotton and Cotton Fibres

Seed cotton	Cotton (*Gossypium*) harvested by picking machines or manually, which has already been separated from the boll and still consists of cotton seeds and fibres.
Cotton fibres	The seed hairs, which are separated from the cotton seeds by ginning machines, are called cotton fibres.
Cotton seeds	Cotton seeds are a by-product of the cotton ginning process.
Gin trash	Gin trash is another by-product that is created during the ginning process. These consist of, among other things, residues of cotton bolls, leaves, leaf stalks and dust particles.
Cotton linters	Before the cotton seeds are further processed in the oil mill, the short hairs attached to them are removed. These hairs are not suitable for the production of cotton fibres and are called cotton linters.
Cottonseed hulls	Before the cotton seeds are pressed, they have to be hulled. In addition to the seeds, the seed hulls are obtained.
Cottonseed oil, crude	"Cottonseed oil, crude" is the vegetable oil produced in the oil mill by pressing and extraction from cotton seeds.
Cottonseed oil	Cottonseed oil is the edible oil that can be used for food purposes after refining.
Cottonseed meal	Cottonseed meal is the by-product produced in the oil mill, which is primarily used in livestock farming as animal feed.

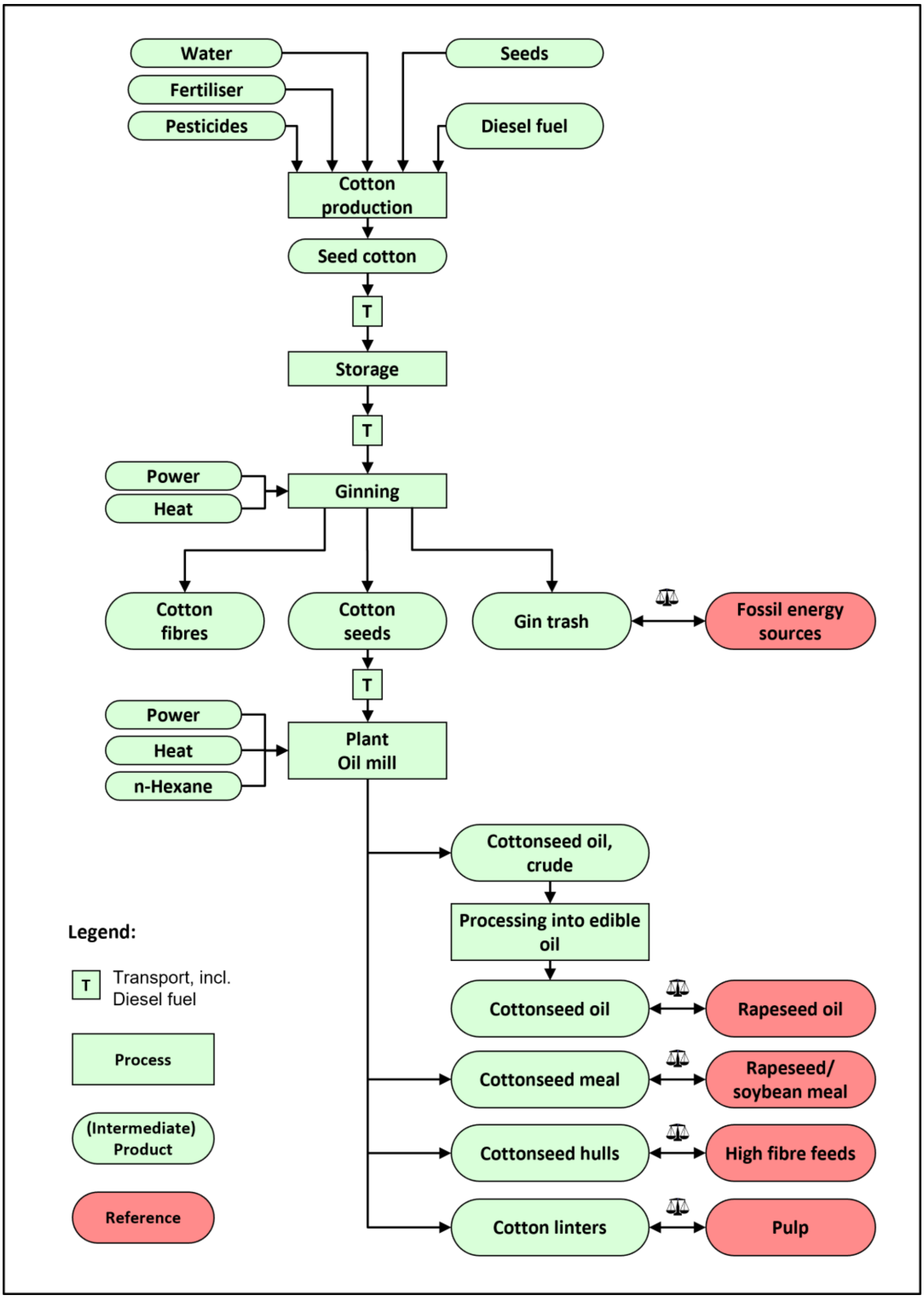

Figure 1. Schematic representation of the production of cotton fibres and their by-products.

3 Input Data

For the calculation of the environmental footprints of cotton products, the following processes and parameters will be considered:

- Agricultural cultivation, including
  - the use of seeds, fertilisers, and pesticides
  - irrigation
  - diesel fuel, and
  - crop yields
- Energy and water requirements for ginning the crop
- Energy, water and chemical use of cotton oil extraction and refining
- Mass balances of the ginning and oil recovery process
- Transport processes between the life cycle stages

The input data in chapters 3.1 to 3.5 are subdivided into the life cycle sections “agricultural cultivation” (conventional and organic), “ginning”, “oil mill” and “oil refining”.

3.1 Conventional Cultivation of Cotton

3.1.1 Yield

In order to relate data on agricultural cultivation to the amount of seed cotton harvested, one must know the ratio between harvested mass and cultivated area, i.e., the yield. Globally, cotton yields vary widely, as do the data in the literature. Therefore, a detailed analysis is necessary.

Based on the latest available data [USDA 2022], Table 1 shows the 5-year average global area under cotton cultivation, production volumes, and yields. The 20 main producing countries produce approx. 96 % of the world's total volume on approx. 92 % of the world's cotton cultivation area (see Table 1). Accordingly, the average yield for cotton fibres (between 2016 and 2020) weighted by cultivated area was 779 and 842 kg $ha^{-1}yr^{-1}$, respectively, worldwide and in the 20 main cultivating countries. This corresponds to a yield of 2.22 t $ha^{-1}yr^{-1}$ seed cotton (worldwide) and 2.41 t $ha^{-1}yr^{-1}$ seed cotton (top 20) (own calculation based on [USDA 2022]), assuming a share of 35 % fibres in seed cotton (see chapter 3.3).

Table 1. Production volume of cotton, area under cultivation, and yield of cotton fibres as well as yield of seed cotton worldwide and in the 20 main producing countries based on the latest available 5-year average (2016-2020). Own conversion of production volumes from million 480 lb bales to million tonnes and calculation of global production, cultivated area shares, and yields. Calculated on the basis of [USDA 2022].

	Country	Production volume [million t]	Share of global production	Cultivated area [million ha]	Share of global cropland	Yield cotton fibres [t $ha^{-1}yr^{-1}$]	Yield seed cotton [t $ha^{-1}yr^{-1}$]
1	India	6.1	24%	12.6	38%	0.49	1.40
2	China	5.8	23%	3.3	10%	1.77	5.06
3	USA	4.0	16%	4.1	13%	0.96	2.76
4	Brazil	2.4	9.4%	1.4	4.2%	1.71	4.88
5	Pakistan	1.5	5.8%	2.4	7.4%	0.61	1.74
6	Uzbekistan	0.78	3.1%	1.1	3.4%	0.71	2.02
7	Türkiye	0.75	3.0%	0.46	1.4%	1.66	4.74
8	Australia	0.62	2.4%	0.37	1.1%	1.82	5.19
9	Greece	0.29	1.2%	0.25	0.8%	1.18	3.37
10	Mexico	0.29	1.1%	0.19	0.6%	1.56	4.47
11	Benin	0.27	1.1%	0.58	1.8%	0.47	1.33
12	Mali	0.24	0.9%	0.60	1.8%	0.40	1.14
13	Argentina	0.24	0.9%	0.35	1.1%	0.68	1.96
14	Turkmenistan	0.24	0.9%	0.56	1.7%	0.43	1.23
15	Burkina Faso	0.22	0.9%	0.66	2.0%	0.34	0.97
16	Ivory Coast	0.19	0.8%	0.38	1.2%	0.50	1.43
17	Myanmar	0.16	0.6%	0.24	0.7%	0.64	1.83
18	Cameroon	0.12	0.5%	0.24	0.7%	0.52	1.47
19	Sudan	0.11	0.4%	0.17	0.5%	0.66	1.89
20	Tajikistan	0.11	0.4%	0.17	0.5%	0.63	1.79
	Total Top 20	*24.5*	*96%*	*30.1*	*92%*	*0.81*	*2.33*
	Worldwide	**25.5**	**100%**	**32.8**	**100%**	**0.78**	**2.22**

These figures are only slightly higher than the results of a LCA study from 2017 commissioned by Cotton Incorporated, reporting data on cultivated area, production, and yield for the three main producing countries China, India and the USA. According to this study, the weighted average is 2.09 t $ha^{-1}yr^{-1}$ seed cotton (own calculation based on [Cotton Inc. 2017]), while the data from [USDA 2022] lead to yields of 2.28 t $ha^{-1}yr^{-1}$ for the top three countries. However, these three countries are only responsible for 63% of the global cotton harvest volume (own calculation based on [USDA 2022]).

The otherwise very valuable FAO agriculture database [FAO 2021] has implausible values for the production data of cotton in China in recent years, which do not match the statistical data from China [National Bureau of Statistics of China 2021]. Therefore, the FAO data are only used for comparison in this study. According to these data, 76.1 million tonnes of seed cotton were produced on average annually over the last 5 years (2016-2020), which corresponds to a global average yield of 2.29 t $ha^{-1}yr^{-1}$ with a cultivated area of 33.2 million ha averaged in the same way (calculation based on [FAO 2021]), i.e. slightly more than the figures derived from [USDA 2022] (2.22 t). Taking the overestimation of the yield data for China for 2019/20 into account [FAO 2021], the resulting yield amounts to 2.15 t $ha^{-1}yr^{-1}$, which is slightly less than the 2.22 t $ha^{-1}yr^{-1}$ derived from [USDA 2022] data. Hence, the FAO data [FAO 2021], corrected by the implausible data for China, confirms the values derived from [USDA 2022].

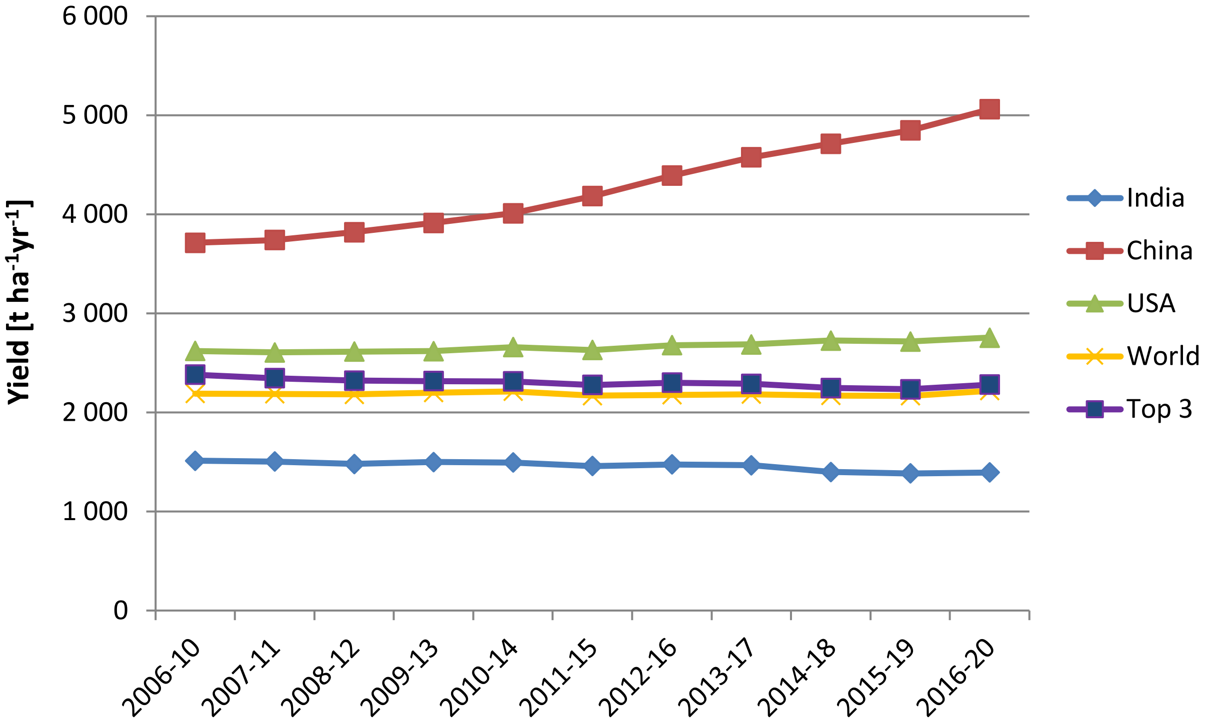

Figure 2. Moving 5-year average of seed cotton yields for the three main producing countries (individually and acreage-weighted average) as well as global mean between 2006 and 2016. Calculated on the basis of [USDA 2022].

It is striking that there has been very little increase in yields over the period 2006 to 2016 (Figure 2): for the top 3 countries India, China and the USA there has even been a decline of 0.42% per annum, while globally the increase has been 0.14% per annum (ten main producing countries: 0.15%, see Figure 5 in the annex). China clearly stands out from this list, having been able to increase its yield by an average of 3.6% annually (own calculation based on [USDA 2022]).

Since the yield increases predicted a few years ago may not materialise in the future and the world market is very much governed by the main producing countries, we use an **average yield of 2.2 t_{FM} $ha^{-1}yr^{-1}$**. At 7.7% water content, this corresponds to 2.03 t_{DM} $ha^{-1}yr^{-1}$. As described in chapter 3.3 seed cotton is divided into 35% fibres, 55% seeds and 10% gin trash. Thus, 0.77 t_{FM} cotton fibres, 1.21 t_{FM} cotton seeds, and 0.22 t_{FM} gin trash is produced per hectare.

A yield increase from 1.6 t $ha^{-1}yr^{-1}$ [Rehm & Espig 1996] to 2.2 t $ha^{-1}yr^{-1}$ over the last decades, corresponding to a rate of 1.3% per year, is plausible.

3.1.2 Land Use

Land use has two aspects in LCA: the direct environmental impact of land use, which is expressed in loss of natural space, and the indirect impact on other environmental effects, especially the greenhouse effect, through changes in land use and biomass stock.

For the calculation of the land footprint according to [Fehrenbach et al. 2019], cotton is assigned hemeroby class VI (most intensive agriculture).

The country-specific environmental burden (emissions of greenhouse gases) resulting from land use and land use change weighted according to production quantities is calculated according to the aLULUC (attributional land use and land use change) method [Fehrenbach et al. 2020]. The results are shown in the Annex (Table 9).

3.1.3 Resources

Fertiliser

Fertiliser quantities can be determined in two ways: either via the nutrient quantities that are removed from the land with the harvested crop and are lost via leaching and denitrification, or via the fertiliser quantities applied, which are reduced by the preceding crop effect. Furthermore, the deposition of nitrogen compounds from the atmosphere must be taken into account, which can reduce the N fertiliser requirement considerably. Due to the very large variation, both approaches are used to determine and compare fertiliser application rates.

First, we analyse the removal of nutrients embodied in the harvested crop. Various published data on nutrient removal from cotton [IPNI 2022; Cain et al. 2007; Smith & Welsh 2018; Mitchell 2011; Rochester et al. 2012] are presented in Table 2. Nitrogen removal ranges from 18 to 64 kg per tonne seed cotton; phosphorus removal ranges from 9 to 28 kg P_2O_5/t, while potassium ranges from 7 to 38 kg K_2O/t. This rather high variation can partly be explained by the different nutrient content of the crop depending on the growing region and the corresponding fertiliser regime, the yield and the species and variety used.

Values measured in field trials (mean values in Table 2 calculated from [Bellaloui et al. 2015]) show N contents in seed cotton of 25 to 30 kg N/t, depending on the variety (with and without fuzz), while P and K are relatively constant at 9.4 kg P_2O_5/t and 9.8 kg K_2O/t seed cotton, respectively. This applies to individual varieties and specific growing conditions and can therefore not be scaled up to global cotton production.
According to Cotton Inc., the amounts of mineral fertiliser used in cotton cultivation vary significantly depending on the growing region (see Table 3). The Cotton Inc. study is cited by recent, peer-reviewed studies (see for example [Lehmann et al. 2019]) and contains the most recent and detailed publicly available data on a range of input data [Cotton Inc. 2017].

Table 2. Nutrients removed from the field in the harvested crop.

Nutrient	IPNI 2022 kg / t_{FM} seed cotton	Cain et al. 2006 kg / t_{FM} seed cotton	Smith & Welsh 2018 kg / t_{FM} seed cotton	Mitchell 2011 kg / t_{FM} seed cotton	Rochester et al. 2012 kg / t_{FM} seed cotton	Bellaloui 2015 kg / t_{FM} seed cotton
N	64	55	54	24	18	27
P_2O_5	28	24	23	10	8	9
K_2O	38	20	19	12	7	10
CaO	n.a.	n.a.	3.7	n.a.	0.8	1.8

Table 3. Fertiliser use in different major growing regions, calculated on the basis of [Cotton Inc. 2017], and parameters set in this study. The quantity of seed cotton refers to fresh matter.

Nutrient	USA kg / t_{FM} seed cotton	China kg / t_{FM} seed cotton	India kg / t_{FM} seed cotton	*Range (by sub-region)* kg / t_{FM} seed cotton	*Mean across all regions** kg / t_{FM} seed cotton	**ifeu 2022** **kg / t_{FM} seed cotton**
N	42	31	60	28 - 63	51	**50**
P_2O_5	16	22	17	6 – 26	18	**20**
K_2O	21	10	2	2 – 40	7	**10**
CaO	n.a.	n.a.	n.a.	-	-	**2**

* Weighted average over all reported sub-regions

The range of applied nutrients in fertilisers corresponds roughly to the respective range of nutrient removal from Table 2. Negative outliers can be explained by fertiliser use below the requirement; in [IPNI 2022], the data source is unclear. Furthermore, the input of nitrogen compounds from the atmosphere must be taken into account, which in most regions is between 10 and 25 kg N $ha^{-1}yr^{-1}$ and may have been neglected by some sources. It is therefore reasonable to assume that the real fertiliser amounts from [Cotton Inc. 2017] and the range of nutrient removal in Table 2 are congruent. Although reported for specific regions, we assume that the fertiliser amounts determined by Cotton Inc. (Table 3) correspond to the nutrient amounts that exactly balance the nutrient removal by the crop and the losses due to leaching and denitrification. Thus, the mean fertiliser use "across all regions" in Table 3 is considered actual fertiliser quantities and – rounded – defined as fertiliser application rates in this paper ("ifeu 2022").

Due to the large variation in the amount of nutrients removed via the harvested crop reported by the different sources (Table 2) no estimations regarding total nitrogen losses through leaching and denitrification will be made. Instead, we use fertiliser application as the basis for further calculations. This is different from other IFEU assessments, which are based on the amount of nutrients removed with the harvest.

Despite the high variation in the data, we will showcase the calculation of nitrogen losses and how to obtain the range of crop nutrient contents. According to [Mitchell 2011], the losses due to leaching and denitrification can amount up to 50%. The nitrogen loss factor, which [Müller-Lindenlauf et al. 2014] determined for Central European conditions is 37% for annual crops. A model describing the loss on a global level does not yet exist, but in many non-European countries, such as the main cotton producer India, agricultural cultivation takes place much more extensively, which is why lower leaching quantities are to be expected due to lower fertiliser use. With regards to airborne nitrogen emissions (NH_3, N_2O, NO and N_2), we use the corresponding factor of 13.3% reported by [Müller-Lindenlauf et al. 2014]. Accordingly, a fertiliser application rate of 50 kg N per t_{FM} crop, 10 kg N deposition $ha^{-1}yr^{-1}$ and a yield of 2.22 t $ha^{-1}yr^{-1}$ result in a maximum nutrient content of 47.2 kg N per t crop and a minimum nutrient content of 27.2 kg N per t crop based on a maximum of 50% N losses according to [Mitchell 2011]. These values are in the range of N crop content (Table 2).

According to [Müller-Lindenlauf et al. 2014] phosphate loss resulting from leaching is about 1 kg PO_4 per hectare of fertilised area (corresponding to 0.75 kg P_2O_5), thus an order of magnitude below the range of P removal, and is therefore applied considering the lack of a globally established approach.

Calcium as a nutrient is not reported by all sources. It is also sometimes unclear whether reported values of calcium quantities are predominantly for soil improvement or whether they reflect actual removal. The range is from 0.8 kg CaO [Rochester et al. 2012] up to 15 kg CaO/t of seed cotton [Ecoinvent 2020]. Since the latter amount corresponds to the applied fertiliser quantity, it may be assumed that this does not refer to the quantity removed, but also includes the regulation of the pH value in the soil. Since calcium fertilisation plays a minor role in the environmental impacts, a slightly rounded value is set here.

Assuming good farming practices, no loss through leaching is set for potassium and calcium. Nutrients such as magnesium, sulphur and others are of secondary importance or are not a limiting factor and therefore not discussed here.

Diesel fuel

According to Cotton Inc., the diesel fuel (DF) required for cultivation in the top three cotton producing countries ranges from 11.8 to 79.7 L $ha^{-1}yr^{-1}$, depending on the growing region [Cotton Inc. 2017]. Averaged by cultivated area, this corresponds to 24.9 L $ha^{-1}yr^{-1}$. These figures are slightly lower than values for organic cultivation (29 L $ha^{-1}yr^{-1}$ provided by [Textile Exchange 2014].). According to Textile Exchange, the range for diesel consumption is very wide, depending on the region of cultivation (2.0 L $ha^{-1}yr^{-1}$ in parts of India to 112 L $ha^{-1}yr^{-1}$ in parts of the USA).

The fuel required for oil crops (excluding oil palm) is between 50 and 65 L $ha^{-1}yr^{-1}$, for wheat about 45-50 L $ha^{-1}yr^{-1}$ [ifeu 2022], and can be compared to the field cultivation of cotton.

Since mechanical harvesting accounts for a large proportion of yield-related fuel consumption, and today much of the cotton (in India and China) is still being harvested manually [Cotton Inc. 2017], a mean value of 40 L $ha^{-1}yr^{-1}$ is applied. The weight- and area-dependent shares are each set at 50% and are based on the yield value of 2.2 t $ha^{-1}yr^{-1}$ derived in 3.1.1. This results, slightly rounded, in a diesel fuel input of 20 L DF $ha^{-1}yr^{-1}$ plus 9.1 L DF/t yield. Considering a yield of 2.2 t_{FM} $ha^{-1}yr^{-1}$ this corresponds to 40 L diesel fuel.

Irrigation

Irrigation data are not only crucial for determining the water footprint of cotton, but also for completing the energy balance, as irrigation requires diesel- or electricity-powered pumps. The necessary energy in turn has an effect on all other environmental impacts.

Cotton cultivation is said to consume very large amounts of water, up to 29,000 L per kg of fibre [Bärlocher et al. 1999]. This cannot be confirmed by current studies. According to Pfister et al. the irrigation water amounts of the ten main producing countries range between 380 and 4,150 L/kg cotton [Pfister et al. 2009]. Accordingly and based on [USDA 2022], irrigation water requirement amounts to a rounded weighted average of 1,880 L/kg, while according to ICAC it is between 0 and 11,900 L/kg cotton or on average 1,930 L based on national means [ICAC 2021a after Lanfranchi & Cline, 2021].

While Ecoinvent assumes a total of 1,980 m^3/ha for artificial irrigation, differentiated by surface water and groundwater [Ecoinvent 2020], [Jans et al. 2020] and [Cotton Inc. 2017] provide a range of 0 - 9,210 m^3 $ha^{-1}yr^{-1}$ and 800 - 9,780 m^3 $ha^{-1}yr^{-1}$, respectively. Given the set yield of 2.2 t/ha, the values published by Pfister are also in this range. The irrigation data published by Pfister et al. for the 20 main producing countries, weighted by production volume, were used to calculate the water footprint.

Since water scarcity varies greatly depending on the growing region and the use of the same amount of water in a very dry region leads to greater environmental damage than in a more humid region, taking water scarcity into account is essential for a holistic assessment of water as a resource in LCAs. This study uses the AWARE method [Boulay et al. 2018] with so-called water scarcity factors to calculate the required amount of irrigation water, which can lead to significantly different water footprints in different regions with comparable irrigation amounts (see Table 10 in the Annex).

Field irrigation requires pumps, which are often powered by diesel generators due to their decentralised location. The Australian cotton industry association CottonInfo provides a value of 1.10 L DF / million L water / m pump pressure [CottonInfo 2015]. Considering a typical pump pressure for most commonly used irrigation systems of between 8 and 35 m [Chen & Baillie 2007]), this corresponds to 0.009-0.039 L DF/ m^3 of water. A very similar consumption of 0.008-0.036 L DF/m^3 water is calculated from the formula suggested by [Chen & Baillie 2007]. Since typical values are assumed here and pump pressure can be higher in some cases due to deeper drilling and other factors, 0.05 L DF per m^3 water is assumed to calculate diesel consumption for irrigation. Depending on the country of origin, the non-renewable cumulative primary energy input of the electricity used and the fuel required for the pumps can be in a similar range. Since this leads to a similar environmental burden for the environmental impact categories examined in this study and no statistically relevant data are available on the proportional distribution of electricity- and diesel-powered pumps for irrigation, 50% of each electricity- and diesel-powered pumps are assumed. The environmental burden from electricity-powered pumps is determined by the country-specific energy mix.

Pesticides

Not only the water demand, but also the pesticide use in cotton cultivation is considered very high by many authors. It is said that up to 25% of the worldwide insecticide and 16% of the pesticide use can be attributed to cotton production (various sources see [Lanfranchi & Cline 2021]). In contrast, according to more recent data, only 10.24% of insecticide and 4.71% of pesticide use are due to cotton production ([ICAC 2021b].

According to Ecoinvent, 3.6 kg $ha^{-1}yr^{-1}$ of pesticides (active substance) are applied in cotton cultivation [Ecoinvent 2020]. As there is no source providing global national-level data on pesticide use in cotton cultivation, assumptions have to be made. Based on country- and area-specific data on pesticide use in agriculture from [ICAC 2021b] and the country-specific share of cotton cultivation in total cultivated area [USDA 2022], we obtained a weighted mean value of 2.3 kg $ha^{-1}yr^{-1}$ active substance. Based on country-specific data on total pesticide use [ICAC 2021b], the proportion of pesticides used in cotton cultivation, and area of cultivation for cotton [USDA 2022], the result is 4.9 kg $ha^{-1}yr^{-1}$. Since the use of pesticides has no relevant effect on the environmental impact categories examined in this LCA, we assume 5 kg $ha^{-1}yr^{-1}$ active substance.

Seeds

According to Ecoinvent, 4 g of cotton seeds are needed to obtain 1 kg of conventional seed cotton [Ecoinvent 2020]. Considering a yield of 2.2 t $ha^{-1}yr^{-1}$, this corresponds to 8.8 kg $ha^{-1}yr^{-1}$ seeds. According to Textile Exchange, between 2 and 35 kg $ha^{-1}yr^{-1}$ seeds are used in organic cotton production, depending on the growing region [Textile Exchange 2014]. Since seeds have no significant influence on the environmental impact categories examined in this LCA, a general application rate of 10 kg $ha^{-1}yr^{-1}$ seeds is assumed for both conventional and organic cultivation.

3.2 Organic Cotton Cultivation

3.2.1 Yield


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In order to obtain meaningful values for the yield of organically grown cotton, we use studies that examine both organic and conventional cotton cultivation. There are a number of studies on organic cotton cultivation in India. This is also where most of the organic cultivation takes place, about 50%, followed by China, Kyrgyzstan and Turkey (12, 12 and 10% respectively) [Textile Exchange 2021]. Forster et al. found in field trials that yields are 7-20% lower than conventional ones [Forster et al. 2013]. According to Eyhorn et al. organic cultivation had a 5% higher yield, averaged over two years, than conventional production [Eyhorn et al. 2007], while other authors indicated yield reductions of 9% [Singh et al. 2019] and 23% across different farm sizes [Riar et al. 2020]. For the USA, the yield of organic cotton cultivation is 34-35% [Swezey et al. 2007; Wakelyn & Chaudhry 2009], for Uganda 15% [Elepu & Ekere 2009] lower than that of conventional cultivation.

On average, a typical yield reduction is therefore between 10 and 25%. Based on an average yield of 2.2 t $ha^{-1}yr^{-1}$ in conventional cultivation, the yields in organic cotton cultivation thus range from 1.65-2.0 t $ha^{-1}yr^{-1}$. The yield provided by Textile Exchange (1.835 t $ha^{-1}yr^{-1}$) also lies within this range [Textile Exchange 2014]. The yield of 1.43 t $ha^{-1}yr^{-1}$ published by Ecoinvent is only based on a single farm in India and therefore not representative [Ecoinvent 2020]. Other yield data also refer to production systems in India and are therefore not representative [Eyhorn et al. 2005, 2007; Riar et al. 2020].

In this LCA, we assume a direct yield of **1.8 t_{FM} $ha^{-1}yr^{-1}$** of seed cotton for organically produced cotton, that is the yield in a cotton growing year, see also next paragraph. This corresponds to a yield reduction of 18% compared to the yield of 2.2 t_{FM} $ha^{-1}yr^{-1}$ assumed for conventional cultivation.

In order to obtain the effectively cultivated area (or effective yield) we have to take into account that no mineral fertilisers are used in organic cotton cultivation. Therefore, we assume that N fertilisation takes place via the integration of legumes in crop rotation (green manuring). For instance, over a four-year crop rotation cycle legume is cultivated during one year, leaving only 3 years of cotton cultivation and therefore cotton yield. The effective yield is calculated from the direct yield and the crop rotation years as follows:

$$E_{\mathrm{eff}} = E_{\mathrm{dir}} \cdot \frac{n_{\mathrm{FF}} - 1}{n_{\mathrm{FF}}}$$

where
E_{eff} is the effective yield considering additional green manuring,
E_{dir} is the direct yield in a year of cotton cultivation,
n_{FF} is the number of years in the crop rotation including the green manure year.

Due to the relatively low N requirement in cotton cultivation (about 100 kg $ha^{-1}yr^{-1}$, cf. 3.1.3), we use a crop rotation cycle of four years as standard scenario (Std). This also takes into account the fact that in organic farming, organic materials, such as compost and residues from agriculture, are often used as soil amendments and may have to be brought back into the soil via an extended crop rotation cycle including green manure to combat soil depletion. A 3- and 5-year cycle (high and low, respectively) is used for assessing sensitivity. Assuming a direct yield of 1.8 t_{FM} $ha^{-1}yr^{-1}$, this results for a 3-, 4- or 5-year cycle in:

- Standard scenario: 1.35 t_{FM} $ha^{-1}yr^{-1}$ effective yield
- Low scenario: 1.20 t_{FM} $ha^{-1}yr^{-1}$ effective yield
- High scenario: 1.44 t_{FM} $ha^{-1}yr^{-1}$ effective yield

3.2.2 Land Use

For the calculation of the land footprint, organic cotton is assigned hemeroby class V due to its lower impact on the diversity of the flora and fauna accompanying arable land and reduced substance inputs compared to conventional cotton production [Fehrenbach et al. 2019; Federal Environment Agency (UBA) 2021].

The environmental burden (emissions of greenhouse gases) resulting from land use and land use change is calculated according to the aLULUC (attributional land use and land use change) method [Fehrenbach et al. 2020] and country-specific production quantities. The country-specific environmental burden by production area and quantity of seed cotton are shown in the Annex (Table 9).

3.2.3 Resources

Fertiliser

In organic cotton cultivation mainly compost and cattle manure are used as fertiliser. In LCAs, the use of farm fertiliser must be considered one by one. In this study, we use cultivated biomass (legumes) for the input of nitrogen. Details are provided in 3.2.1. For the other mineral nutrients, we assign mineral fertiliser to cover the demand, taking into account nutrient removal and depletion elsewhere. The demand for phosphorus, potassium and calcium fertiliser is consequently analogous to conventional cultivation (see Table 9).

Diesel fuel

The fuel requirement for field cultivation of organic cotton is derived from conventional cultivation. Fuel consumption is both area- and yield-dependent. Tillage and sowing are among the area-dependent expenses. Fertiliser application and harvesting are predominantly yield-dependent.

In the case of annual crops, such as wheat, sunflowers or rapeseed, the area-dependent expenses are responsible for 10-20% of the fuel demand, assuming average yields [ifeu 2022]. For cotton, we assume 20% of area-related fuel demand with an uncertainty range of 50%.

Due to green manuring, diesel fuel consumption is slightly increased in organic farming. However, due to the relatively simple field cultivation, the additional quantity required does not contribute significantly to the increase in the environmental burden (the total diesel fuel required is responsible for only 1% of the total greenhouse gas emissions). Moreover, the degree of mechanisation of cultivation is not related to whether organic or conventional farming methods are used. For this reason, and since the amount of diesel fuel has no significant effect on the CO_2 footprint, the use of diesel fuel in organic farming is assumed to be the same as in conventional farming, irrespective of the degree of mechanisation and the small additional input required for green manuring (see 3.1.3).

Irrigation

Organically grown cotton is often considered more sustainable in terms of water consumption. For example, according to Textile Exchange, organic cotton cultivation requires 91% less water than conventional cultivation, a figure that has been cited by a number of authors [Soil Association 2015; Szmydke-Cacciapalle 2018; Delate et al. 2020]. Other sources also report lower water requirements, including [La Rosa & Grammatikos 2019]. According to [Lanfranchi & Cline 2021], however, the cotton fields studied by Textile Exchange included organic cotton cultivation predominantly on non-irrigated fields and predominantly irrigated conventional production. At the same time, they point out that there is in fact no evidence indicating a reduced need for irrigation of organic cotton. Textile Exchange no longer claims the 91% water reduction.

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There is evidence, however, that organic cotton is on average more often grown on non-irrigated land than conventional cotton. According to [Textile Exchange 2015], 80% of organic cotton is grown in rainfed agriculture, while [ICAC 2021b] provides a global average (of conventional and organic cotton) of 52% rainfed cultivation. Based on current data on the cultivated area of organic cotton [Textile Exchange 2021] and the country-specific shares of rainfed cultivation for all types of cotton [ICAC 2021b] it is possible to estimate the share of organic cotton produced in rainfed agriculture worldwide. Accordingly, and depending on how the data gaps are filled, 71 to 77%, or 74% if the average share of rainfed cultivation is used, of organic cotton is produced worldwide in rainfed agriculture (see Table 4 on the next page) and thus a significantly higher share than the value of 52% provided by [ICAC 2021b].

Furthermore, it has to be considered that the yield of organic cotton is 1.8 t/ha, i.e., 82% of the conventional yield (2.2 t/h). Besides, periods of legume cultivation need to be taken into account, which, in organic farming, serve as green manure and which, according to [Pfister et al. 2009], receive a similar level of irrigation as cotton. Assuming a constant level of irrigation, this results in an average yield reduction of 25% and therefore in 61% of the conventional yield. The yield-related water requirement thus increases to 163% of the conventional water requirement.

However, since the share of irrigated area in organic farming is only 23-29% compared to 48% in conventional farming, the water requirement decreases to 38-47% of the irrigation water required in conventional cotton cultivation. Crop rotation results in reduced yields of 67-80%, and therefore increases the water requirement to 75-110% of the amount of irrigation water in conventional production. Limitations of the assessment include the fact that some of the fields are only partially irrigated and the large variability of the amount of irrigation water due to climatic reasons, which make exact quantification (even at an accuracy of 10%) impossible.

Table 4. Shares of organic cultivation in the global cultivated area of cotton according to [Textile Exchange 2021] and shares of rainfed cotton cultivation in total cultivation of (conventionally and organically produced) cotton according to [ICAC 2021b] worldwide (weighted mean from all producing countries) and for the 20 main producing countries.

	Country	Share in global cultivated area of cotton	Share of rainfed area in total cultivated area (conv. and organic)
1	India	48.5 %	65 %
2	Tanzania	26.3 %	100 %
3	Uganda	6.8 %	100 %
4	Kyrgyzstan	3.1 %	52 %*
5	China	2.7 %	2 %
6	Mali	2.1 %	100 %
7	Brazil	2.1 %	87 %
8	USA	2.0 %	63 %
9	Türkiye	2.0 %	2 %
10	Tajikistan	1.4 %	52 %*
11	Benin	1.2 %	100 %
12	Burkina Faso	0.7 %	52 %*
13	Pakistan	0.5 %	0 %
14	Greece	0.4 %	7 %
15	Peru	0.16 %	52 %*
16	Egypt	0.03 %	0 %
17	Uzbekistan	0.03 %	0 %
18	Ethiopia	0.03 %	98 %
19	Myanmar	0.01 %	98 %
20	Thailand	0.01 %	52 %*
	Worldwide	**100.0** %	**74** %

* In the absence of available input data, the world average (conventional and organic) according to [ICAC 2021b] was used here.

Due to the uncertainty related to irrigation water amounts in organic cotton production and the fact that the amount of water needed for irrigation of organic cotton is in the range of that of conventional cotton depending on the boundary conditions, the specific irrigation amount for organic cotton per kg fibre is set equal to the irrigation for conventional cotton.

The country-specific water requirements for organic cotton correspond to the ones for conventional cotton, even though this neglects the lower yield of organic cotton. We chose this approach, as currently only case studies in certain countries or regions are available (e.g. [Soil Association 2015; Szmydke-Cacca [Soil Association 2015; Szmydke-Cacciapalle 2018; Delate et al. 2020]), but no statistically relevant studies for all cotton producing countries based on comparable conditions for both types of cultivation. For future calculations, new studies may allow for more precise country-specific water requirements.

Pesticides

In organic farming, synthetically produced pesticides must not be used. Pest control is either not done at all (a reason for yield reductions), by mechanical or other physical methods, or with the help of natural pesticides. Compared to chemical pesticides, the production of natural pesticides involves only a fraction of the environmental burden and is therefore negligible, which is why the cultivation of organic cotton is considered without pesticide application.

Seeds

The use of seeds in organic farming is equated with the use of seeds in conventional farming and amounts to 10.0 kg $ha^{-1}yr^{-1}$.

3.3 Ginning

When the seed cotton is ginned, the cotton fibres are separated from the cotton seed. In the most commonly used cotton harvesting methods (picking machines and hand picking), the bolls remain on the cotton plant and seeds and fibres are harvested without a boll [Cotton Inc. 2020]. Only in certain climatic regions, specific cultivars such as storm-resistant varieties are harvested with the boll by mechanical stripping. As this only accounts for a small proportion of the total harvest, only the harvest of fibres and seeds without bolls is considered for the LCA in both conventional and organic cultivation. The bolls remain in the field. However, certain impurities remain in the seed cotton, which must be separated out in ginning machines ("gin trash") (see chapter 2.2).

The seed cotton is first dried and cleaned before the separation of the components takes place in the ginning machine. According to Rehm and Espig, the proportion of cotton fibre in the seed cotton "in good upland varieties" is at least 35% to more than 40% [Rehm & Espig 1996]. Textile Exchange reports a fibre yield of 35%, Haque of 36% after ginning [Textile Exchange 2014; Haque et al. 2021]. Both specify an amount of 11% gin trash, resulting in a cotton seed yield of 53% and 54%, respectively. The data used in Ecoinvent show a very similar ratio of 38% cotton fibres and 62% cotton seeds [Ecoinvent 2020]), but do not take the gin trash into account. According to FAO data (on FAO statistics, cf. chapter 3.1.1), the average shares of the main producing countries (excluding implausible values) are 35% cotton fibres, 57% cotton seeds and 8% gin trash. The respective values range from 32-37%, 48-66% and 2-15% (own calculations on the basis of [FAO 2021]). Since the degree of mechanisation and thus the degree of impurities in the harvested material is increasing, we assume a value of 10% gin

trash, which is slightly higher than FAO's average value and slightly lower than the values provided by [Textile Exchange 2014; Haque et al. 2021].

Thus, in this study, we assume 35% cotton fibres, 55% cotton seeds and 10% gin trash.

Water content and calorific values

Ecoinvent provides the following water content [Ecoinvent 2020]:

- Seed cotton: 7.7%
- Cotton fibres: 6.4%
- Cotton seeds: 8.4%

These values are plausible and are used in this study.

No data are available in the literature for gin trash. Therefore, we assume the water content of the cotton seed for its use as bioenergy sources and the energy content of cotton, which is, according to [Blanke 2013] 15.5 MJ/kg (H_u).

Energy demand

The electricity demand of the ginning process is 0.156 kWh/kg cotton fibres (corresponding to 59 kWh/t seed cotton) according to Ecoinvent and therefore close to the 57 kWh/t seed cotton provided by [Textile Exchange 2014]. For this study, we use the mean value. The Ecoinvent data also include the drying of the fibres and the pressing of the loose cotton fibres into compact bales using a hydraulic press. For this, Ecoinvent reports a heat demand of 0.103 MJ/kg cotton fibres (corresponding to 39 MJ/t seed cotton) [Ecoinvent 2020]. For the ginning process, we therefore assume 58 kWh of electrical energy / t of seed cotton and 39 MJ of steam / t of seed cotton for the LCA.

3.4 Oil Mill

The cotton seeds produced during the cultivation of cotton is pressed in oil mills to produce crude cottonseed oil, with cottonseed meal as a by-product. According to Rehm and Espig, 0.25 t of cottonseed oil can be obtained from 1 t of cotton seeds, while 0.35 t of cottonseed hulls, 0.35 t of cottonseed meal and 0.05 t of cotton linters are produced in the process [Rehm & Espig 1996]. The Ecoinvent data are based on an error in the mass balance, which is why we use the values from Rehm & Espig. The data on electricity, heat and chemicals required for the operation of the cotton oil mill are based on the data for rapeseed oil mills in ifeu's internal database [ifeu 2022].


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Crude protein content

While Rehm & Espig report a crude protein content of more than 40% (fresh matter) [Rehm & Espig 1996], Bernard indicates a crude protein content of 48.4% (dry matter) at 90.6% dry matter (corresponds to 43.9% in fresh matter) [Bernard 2002]. Since Rehm & Espig assume a crude protein content of more than 40%, the 48.4% crude protein (dry matter) provided by Bernard is set.

Water content and calorific values

- Cottonseed hulls:
  - Moisture content: 9.7% [TNO 2021]
  - Calorific value (fresh): 15.56 MJ/kg [TNO 2021]
  - Calorific value (dry): 17.49 MJ/kg [TNO 2021]
- Cottonseed meal:
  - Moisture content: 9.4% [Bernard 2002]
- Cottonseed oil:
  - defined as anhydrous
- Cotton linters:
  - see cotton fibres, i.e. 6.4% [Ecoinvent 2020]

Reference flows

Cottonseed meal is used as feed in livestock farming because of its high protein content [Heuzé et al. 2019]. Cottonseed hulls can be pelletised and used as a bioenergy source [Heuzé et al. 2015], but are usually added to cottonseed meal or otherwise used as a high-fibre animal feed. Due to its high cellulose content, cotton linters is used for the production of cellulose derivatives in the chemical industry [Deutscher Fachverlag 2021; WGC 2021].

Table 5. Mass balance of cottonseed oil production from cotton seeds, after [Rehm & Espig 1996] incl. by-products.

Output	Share [%]	Use	Reference product
Cottonseed hulls	35	Bioenergy as pellets	Fossil marginal energy mix
Cottonseed oil	25	Food (after refining)	Rapeseed oil (soybean oil)
Cottonseed meal	35	Cattle feed (instead of rapeseed meal) Crude protein content: 48.4 % in dry matter	Soybean meal
Cotton linters	5	Cellulose	Wood cellulose

3.5 Oil Refining

The crude cottonseed oil is refined into edible oil. The data for this process is based on the refining of rapeseed oil in the ifeu internal database [ifeu 2022].

4 Environmental Footprints of Seed Cotton and Cotton Fibre

4.1 Results for Conventional and Organic Cotton Fibres

The results of the four environmental footprints of conventional and organic cotton fibres are shown in Table 6.

Table 6. Environmental footprints of conventionally and organically grown cotton fibres.

		CO_2 footprint [kg CO_2 eq./ kg_{FM} fibres]	**Land footprint** [m^2 yr DNP/ kg_{FM} fibres]	**Water footprint** [m^3 H_2O eq./ kg_{FM} fibres]	**Phosphate footprint** [g phosphate rock eq./ kg_{FM} fibres]
Conventional		2.7	4.4	370	150
Organic	Std	2.3	3.9	370	160
	Low	2.5	4.6	370	160
	High	2.2	3.5	370	160

4.2 Excursus: Comparison of Conventional and Organic Cotton Fibres

When comparing the individual environmental impacts of conventionally and organically grown cotton, the results are mixed. While the water footprints of both conventional and organic cotton fibres are 370 m^3 H_2O eq./kg fibres and the phosphate footprint of organic cotton fibres is only slightly higher than the value of conventional cotton fibres, the greenhouse effect and the land footprint show clear differences. The CO_2 footprint of organic cotton fibres, at 2.3 kg CO_2 eq./kg fibres, is visibly lower than that of conventional fibres (2.7 kg CO_2 eq./kg fibres). In addition, organic cotton also shows advantages in terms of its land footprint (3.9 [organic] compared to 4.4 m^2 yr natural land/kg fibres [conventional]). Figure 3 shows the environmental impact by life cycle stages.

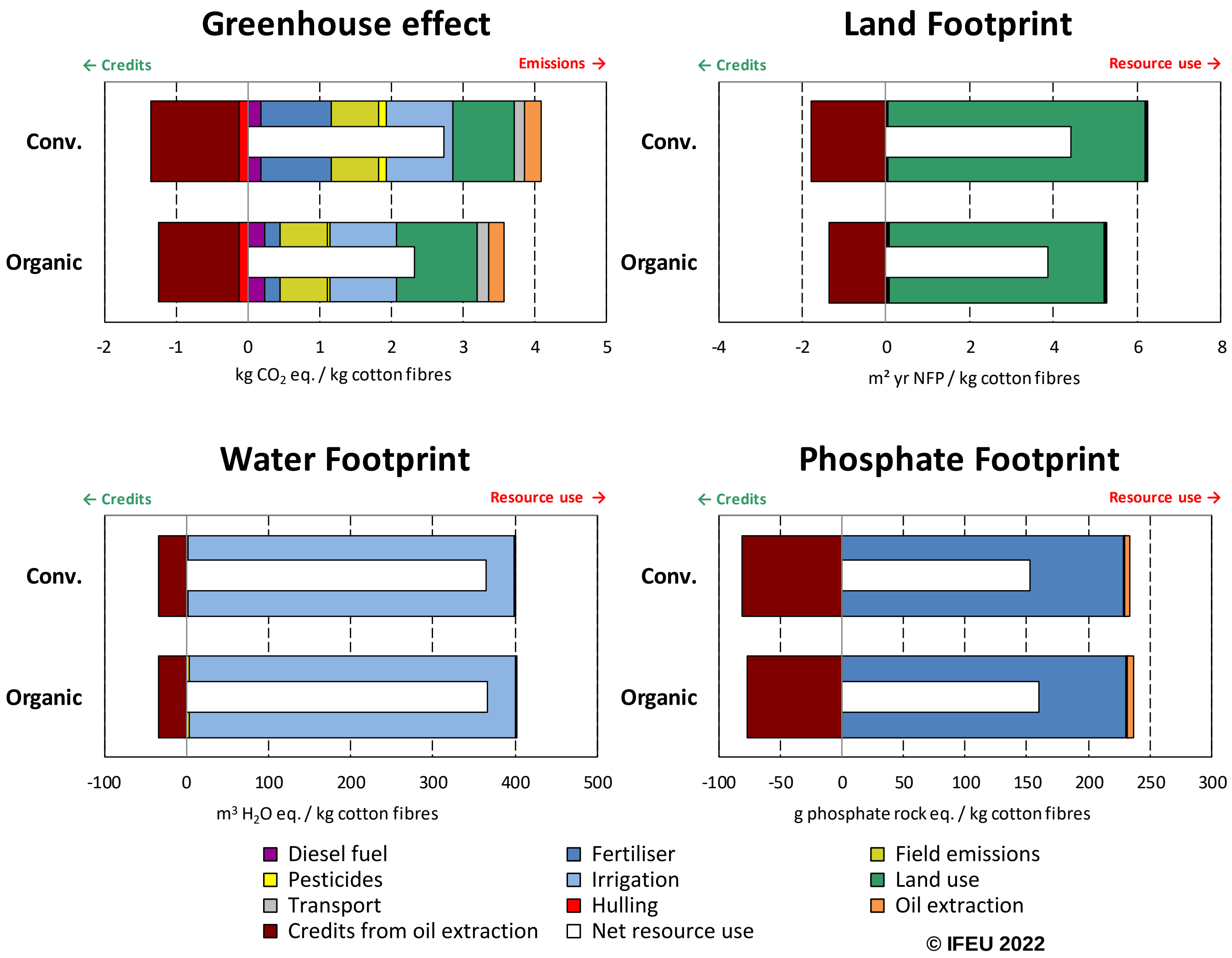

Figure 3. Environmental footprints of conventional and organically grown cotton fibres (fresh matter).

The main factors influencing the greenhouse effect of cotton fibres are fertiliser production and field emissions (for conventional cotton), land use and land use changes as well as irrigation. The share of fertiliser production and field use for conventional cotton fibres is significantly higher than for organic cotton. The lower CO_2 footprint of organic cotton fibres in contrast to conventional cotton fibres can be explained primarily by the lower use of fertilisers. The higher specific greenhouse gas emissions caused by the lower yield of organic cotton due to land use and land use changes do not outweigh the additional emissions from fertiliser production in conventional cotton production. Therefore, the use of organically grown cotton is more advantageous from a climate perspective. In addition, organic cultivation provides greater ecosystem services, which have a positive impact on the land footprint. The phosphate footprint of cotton fibres is almost exclusively due to the use of fertilisers.

The LCA results show that organically grown cotton has both advantages and disadvantages compared to conventional cotton, with the advantages clearly outweighing the disadvantages. While neither of the two types of cultivation shows advantages in terms of water footprint, organically grown cotton performs better in terms of greenhouse effect and land footprint.

4.3 Excursus: Results for Seed Cotton

The results of the four environmental footprints of seed cotton (conventional and organic) are shown in Table 7.

Table 7. Environmental footprints of conventional and organic seed cotton.

Seed cotton (fresh matter)	CO_2 footprint	Land Footprint	Water Footprint	Phosphate Footprint
	[kg CO_2 eq./kg]	[m^2 yr DNP/kg]	[m^3 H_2O eq./kg]	[g phosphate rock eq./kg]
Conventional	1.3	2.2	140	80
Organic	1.1	1.8	140	81

4.4 Excursus: Economic Allocation

Two different methods can be used for the assessment of by-products in LCAs: system expansion and allocation. According to ISO 14040/14044, allocation should only be used if system expansion is not possible or would go beyond the scope of the analysis. System expansion using a substitution approach provides a more realistic estimate of environmental impacts and is therefore preferable and used in this study.
In this subchapter, we use allocation to demonstrate differences in results compared to system expansion. Of the many different possible allocation criteria, such as energy-related, mass-related or economic allocation, we use allocation according to economic criteria as one of the most common allocation methods for non-energy-related questions.

The ginning of the seed cotton results in three products: cotton fibres, cotton seeds, and gin trash. The environmental burden of the seed cotton can therefore be allocated to the different products weighted according to the respective market prices. Often, fees are paid for the disposal of gin trash, which is why they have a theoretical negative market price. Other potential usages are the disposal on the field as mulch or compost, incineration and, in some cases, the energetic use during ginning [Haque et al. 2021; Wilde et al. 2010]. For the few cases where gin trash is sold for energy purposes, no data on sales prices are available. For this reason, the price relationship between cotton fibres and seeds is considered in the economic allocation and the environmental burden is divided between these two economically relevant products (Figure 4). First, we use the market prices of the last ten years (2011 – 2020) for the economic allocation. The prices for cotton fibres according to the Cotlook A Index represent the international cotton market and were taken from Indexmundi [Indexmundi 2021]. Data on cotton seed prices were provided by USDA [USDA 2021].

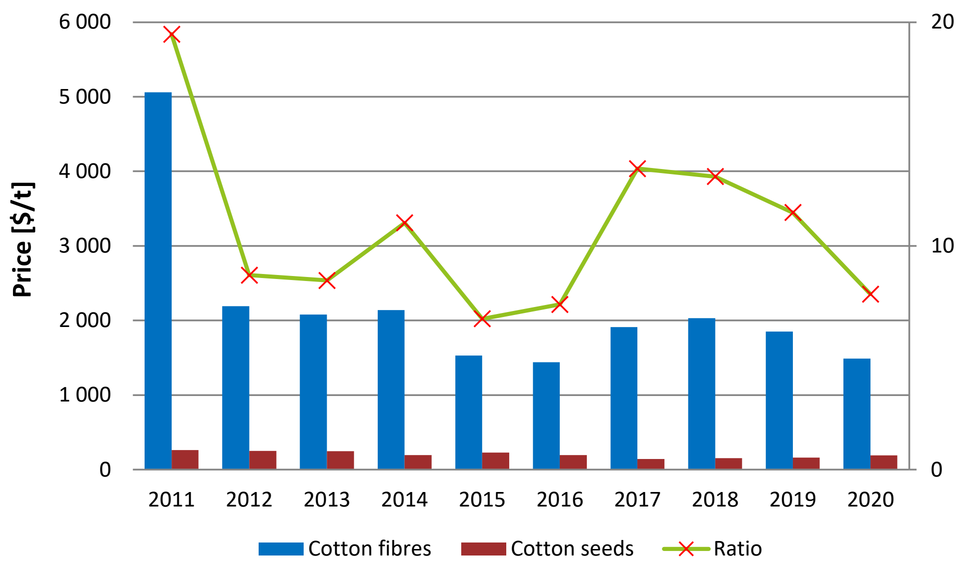

Figure 4. World market prices for cotton fibres and seeds (2011 - 2020) according to [Indexmundi 2021; USDA 2021].

Prices for cotton fibre ranged between $1140 and $5060 per tonne from 2011 to 2020, with the 2011 price affected by the cotton crisis in 2010 and 2011. The price of cotton seeds ranged between $142 and $260 per tonne. The ratio of fibre price to seed price ranged from 6.7 to 19.5, but the high value is also due to a relatively high fibre price in 2011.

Taking the respective average value from the years 2011 to 2020 as the price for cotton fibres and cotton seeds, we obtain a price ratio of 10.7. However, in order to avoid outliers (cotton crisis), the largest and smallest values from each of the 10 years are left out, resulting in an average price ratio of approximately 9.5. This results in allocation factors of 0.86 and 0.14, respectively. Table 8 shows a comparison of the environmental footprints of cotton fibres (conventional cultivation) calculated according to a) the substitution approach and b) economic allocation.

Table 8. Comparison of the environmental footprints of cotton fibres from conventional cultivation calculated according to substitution and economic allocation.

Cotton fibres, conventional	CO_2 footprint [kg CO_2 eq./kg]	Land Footprint [m^2 yr DNP/kg]	Water Footprint [m^3 H_2O eq./kg]	Phosphate Footprint [g phosphate rock eq./kg]
System expansion (“substitution”)	2.7	4.4	370	150
Economic allocation	3.4	5.3	340	200

The environmental burden from cotton fibres is up to approximately 30% higher when applying economic allocation as compared to the substitution approach. This can largely be explained by the credits from reference flows (oil extraction) in the system expansion, but also by the significantly higher market price of the fibres compared to the seeds. The fact that the water footprint is smaller with allocation than with substitution is due to the lower irrigation level of the replaced oil crops.

4.5 Comparison to Other Literature Sources

According to Cotton Inc., the CO_2 footprint of cotton fibres is 1.3 kg CO_2 eq./kg [Cotton Inc. 2017]. Cotton Inc. does not differentiate between conventional and organic cotton fibres and does not include GHG emissions from land use and land use change, which explains the significantly smaller value compared to the value of 2.7 kg CO_2 eq. calculated in this study. Ecoinvent sets the greenhouse effect from conventional cotton fibres at 4.1 kg CO_2 eq./kg, which is significantly higher than the value determined in this study [Ecoinvent 2020]. The reason for this is the use of economic allocation by Ecoinvent in contrast to the methodology (system expansion) used here. In the excursus on economic allocation (see chapter 4.4), we showed that the environmental footprints of cotton fibres are up to 30% larger when using economic allocation compared to the substitution approach. According to a study by the consultancy Anthesis for the Better Cotton Initiative, the five main producing countries of "Better Cotton" have an average CO_2 footprint of 2.9 kg CO_2 eq./kg cotton [Morris 2021]. There, the environmental burden was assessed using economic allocation between cotton fibres and seeds, similar to the approach used by Ecoinvent. The country-specific figures between 1.9 (USA) and 4.1 kg CO_2 eq./kg cotton (India) cannot be reproduced, as relevant input data such as the use of fertilisers and their upstream chains are not available.

According to Ecoinvent, 5.8 m^2 yr (conventional) or 15.0 m^2 yr (organic) of land is required to produce 1 kg of cotton fibre [Ecoinvent 2020]. Cotton Inc. provides a land area requirement of 10.6 m^2 yr without further differentiation [Cotton Inc. 2017]. The land footprints determined in this study were calculated including a weighting of the land according to its respective distance to a natural state. Therefore, a comparison between these values and previously published data on land footprints is limited. Excluding the weighting, the land footprints calculated in this study are slightly lower compared to the values provided by Ecoinvent. This is plausible due to yield increases.

The water demand for the production of cotton fibres given in previously published literature only includes water for irrigation and further production stages, but does not take water scarcity factors according to the AWARE method into account [Boulay et al. 2018; Cotton Inc. 2017; Ecoinvent 2020; Jans et al. 2020]. Thus, literature values on the water footprint of cotton are not directly comparable with the data published here. However, the consideration of water scarcity is essential for a holistic assessment of water resources in LCAs and should become a methodological standard in the future.

Existing literature on LCAs of cotton and cotton fibres do not provide information on phosphate demand. Thus, the values published here represent the first assessment of phosphate use in cotton production.

5 Scientific Evaluation and Transferability of the Results

In this publication, different environmental footprints were calculated for cotton and cotton fibres from conventional and organic cultivation, respectively, both for individual cultivating countries and for a weighted world average.

Scientific evaluation

The results for cotton (seed cotton and cotton fibres) are based on the latest methods for calculating environmental footprints. Therefore, the results represent the latest and best available scientific knowledge and can be used to address questions or conclusions with comparable boundary conditions. The results do not only include the CO_2 footprint, but also several other environmental footprints, such as water and land footprints, which are not represented in many other literature sources, or are represented only partially or with outdated methods and therefore cannot be used consistently.

Applicability and transferability of the results

The data presented here can be utilised in several ways: It can be used directly as "typical" life cycle inventory data for LCAs, for the derivation of further environmental variables, or to answer specific research questions. Since all LCA-relevant input data are available for both the cotton fibres and the by-products, the user can carry out a large number of specific individual analyses. For example, the data can be effectively utilised to calculate the environmental impacts of textile production.

Other environmental impacts that are often analysed in LCAs (e.g., acidification, ozone depletion, or eutrophication) can be easily assessed using the system boundaries and input data reported here.

For some, specific questions, the results of this study may not be suitable or directly transferable. For example, the degree of mechanisation and thus the need for diesel fuel in the cotton harvest is not specified according to the individual countries. Another example is the correlation between irrigation and yield, which must be addressed if analyses are to be made for individual locations by establishing a corresponding function between these variables. Some questions can be addressed with the *general* input data reported here (e.g., fertiliser and pesticide demand, aLULUC – attributional land use and land use change, or the relationship between irrigation and the respective country-specific water footprint); others require *specific* input data derived from the methodological tools described in this study.

A transfer of the results to other, related subjects, e.g., for a comparison of (conventional or organic) cotton cultivation alongside the cultivation of *other* fibre plants, or for assessing the environmental impacts of an atypical use of the by-products, is not possible, but was also not the focus of this analysis.

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7 Annex

This annex shows average cotton yields of the main producing countries, overviews of country-specific greenhouse gas emissions from land use and land use change (LULUC), and country-specific irrigation volumes and water footprints for the production of seed cotton.

Figure 5 represents a more detailed version of Figure 2 in chapter 3.1.1 It shows the 5-year moving average of yields over the period 2006 to 2020 for the ten main producing countries and the respective global average.

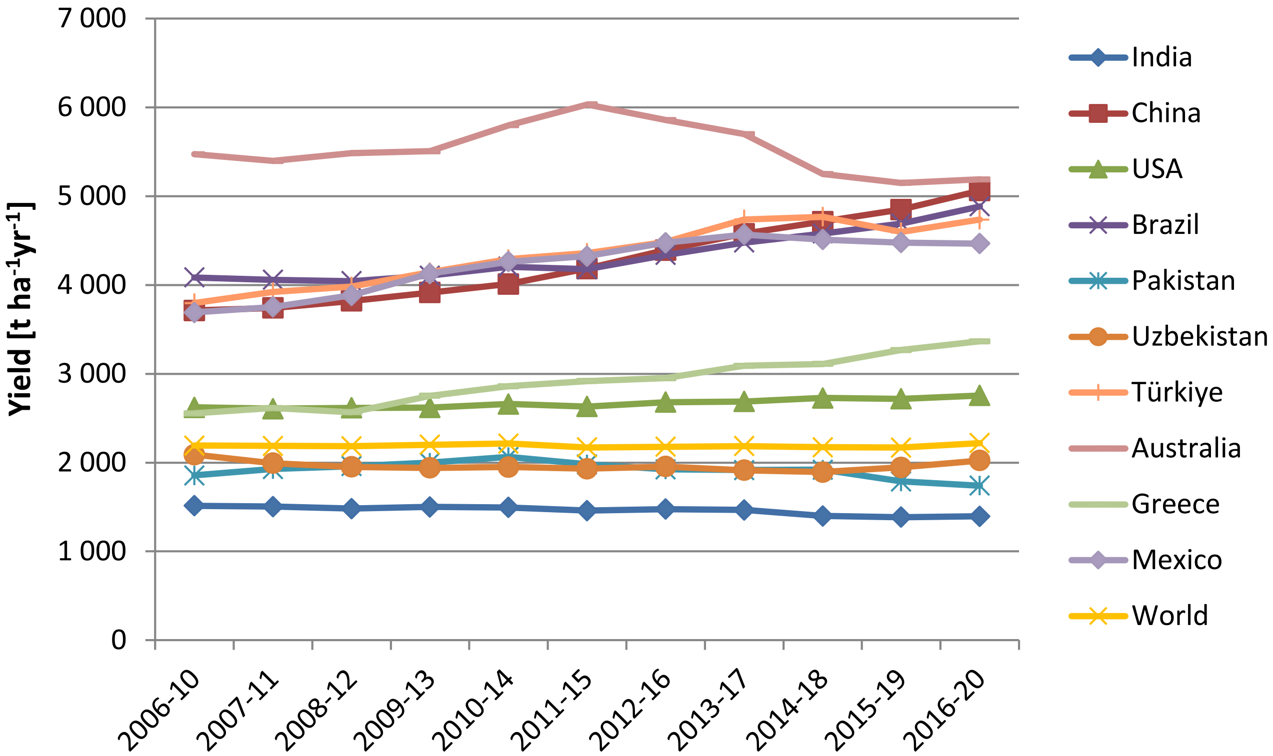

Figure 5. Moving 5-year average of cotton yields (seed cotton) of the ten main producing countries and globally since 2006. Calculated on the basis of [USDA 2022].

Table 9 and Table 10 show the country-specific greenhouse gas emissions due to land use and land use change (LULUC) and the country-specific irrigation volumes and water footprints for the production of seed cotton, respectively. The greenhouse gases generated due to land use and land use change were calculated according to the aLULUC method [Fehrenbach et al. 2020] and weighted according to country-specific production volumes. Water footprints were determined according to the AWARE method [Boulay et al. 2018] depending on the country-specific water scarcity.

Table 9. Overview of country-specific greenhouse gas emissions from land use and land use change (aLULUC), based on cropland cover (ha yr), the production of 1 t_{FM} of conventional and organic seed cotton in the ten main producing countries for the latest available 5-year average (2016-2020). Own calculation based on yields from [USDA 2022] and aLULUC factors from [Fehrenbach et al. 2020].

	Country	aLULUC per cropland cover [kg CO_2 eq. / (ha yr)]	aLULUC in conv. cultivation [kg CO_2 eq. / t seed cotton]	aLULUC in organic cultivation [kg CO_2 eq. / t of seed cotton]
1	India	26	19	31
2	China	24	5	8
3	USA	203	74	120
4	Brazil	5,508	1,128	1,838
5	Pakistan	412	237	386
6	Uzbekistan	0	0	0
7	Türkiye	0	0	0
8	Australia	20	4	6
9	Greece	572	170	277
10	Mexico	0	0	0
11	Benin	3,281	2,466	4,019
12	Mali	1,444	1,263	2,058
13	Argentina	1,878	960	1,565
14	Turkmenistan	0	0	0
15	Burkina Faso	2,174	2,246	3,661
16	Ivory Coast	1,072	749	1,221
17	Myanmar	7,747	4,226	6,887
18	Cameroon	14,276	9,679	15,774
19	Sudan	1.000	530	864
20	Tajikistan	250	140	228
	Worldwide	**693**	**298**	**485**

Table 10. Overview of country-specific irrigation amounts and water footprints for the production of 1 kg_{FM} seed cotton. Own calculation based on irrigation data from [Pfister et al. 2009]. The water footprint was calculated according to the AWARE method [Boulay et al. 2018].

	Country	**Irrigation quantity [m^3 / kg]**	**Water footprint [m^3 H_2O eq. / kg]**
1	India	3.7	242
2	China	0.7	66
3	USA	1.7	104
4	Brazil	0.4	2
5	Pakistan	2.9	290
6	Uzbekistan	2.8	347
7	Türkiye	0.9	104
8	Australia	0.6	81
9	Greece	0.8	112
10	Mexico	1.4	111
11	Benin	1.4	15
12	Mali	1.6	52
13	Argentina	1.0	77
14	Turkmenistan	4.2	471
15	Burkina Faso	1.5	52
16	Ivory Coast	0.7	9
17	Myanmar	0.7	8
18	Cameroon	0.9	21
19	Sudan	2.3	243
20	Tajikistan	2.1	254
	Worldwide	1.9	140

8 Abbreviations

aLULUC	Attributional Land Use and Land Use Change
CaO	Calcium oxide, fertiliser
CH_4	Methane
CO_2	Carbon dioxide
conv.	conventional cultivation
DF	Diesel fuel
DM	Dry matter
DNP	*Distance-to-Nature-Potential*, according to [Fehrenbach et al. 2019]
eq.	Equivalent
FM	Fresh matter
g	Gram
GHG	Greenhouse gas
H_2O	Water
ha	Hectare
kg	Kilogram
kWh	Kilowatt hour
L	Litre
lb	Pound, 480 lb = 217,724 kg
LCA	Life Cycle Assessment
m, m^2, m^3	Metre, square metre, cubic metre
MJ	Megajoule
N	Nitrogen, fertiliser
n.a.	Not applicable
N_2O	Nitrous oxide, laughing gas
P_2O_5	Phosphate (fertiliser)
PO_4	Phosphate (emission)
Std	Standard
t	Tonne
Top 20	20 main cotton producing countries (largest production)
Top 3	3 main cotton producing countries (largest production)
yr	Year