CHALMERS
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Biodiversity Impact Assessment of Conventional and Organic Cotton

A Comparison Using Three Different Biodiversity Quantification Models in LCA

Master's thesis in Industrial Ecology

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Gothenburg, Sweden 2024
www.chalmers.se
Report No. E2023:155

Master's thesis 2024

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Abstract

Anthropogenic activities have led to a decline of nature's ecosystems and biodiversity. The textile industry has contributed to this, especially through conventional cotton fiber production. Acknowledging humans' impact on biodiversity and the industries contributing, there is a need for established models to quantify biodiversity impacts to enhance transparency in the supply chain for mitigation and responsible consumption, aligning with global efforts for biodiversity conservation.

This study aimed to examine the cotton cultivation process and its impacts on biodiversity. This was done through a life cycle assessment (LCA) that compared conventional and organic cotton cultivation in Turkey. Additionally, three different impact assessment methods were used and compared to establish aspects of the models important to capture biodiversity loss and how the models can be developed. The models were ReCiPe2016, a widely applied model that covers multiple impacts and biodiversity damage pathways, and two models measuring biodiversity land use impacts, Chaudhary & Brooks (C&B) that factors in levels of land use intensity, and the Habitat Fragmentation model (HF) that includes impacts from fragmentation.

The results show that the cumulative impact assessed by ReCiPe2016 revealed a greater environmental impact for conventional cotton. Land use significantly affects both systems, with organic cotton showing a larger impact. The conventional cotton production showed a higher impact from toxicity, climate change, and water use, highlighting concerns about fertilization production, use, and irrigation.

Despite land use intensity considerations in C&B, the yield difference remains a crucial factor. The study suggests the need for additional models considering ecosystem multifunctionality to address biodiversity impacts between organic and conventional agriculture. Following the results from the HF model, it is proposed to examine fragmentation effects as an attribute of land use intensity. Integrating models like C&B and HF into operational models is crucial for industry and research, promoting responsible and sustainable practices to ensure comprehensive biodiversity impact coverage in life cycle assessments.

Keywords: Life Cycle Assessment, cotton cultivation, biodiversity, methods of impact assessment

Acknowledgements

This thesis was linked to the project *Calimero* (Industry CAse Studies AnaLysis To IMprove EnviROnmental Performance And Sustainability Of Bio-Based Industrial Processes) with project number 101060546 funded by The European Union.

I want to express my gratitude to the people who have supported me throughout this thesis. I want to thank my supervisor Tomas Rydberg, together with Josefine Neuwirth and Emke Vrasdonk at IVL, for teaching me the ways of Life Cycle Assessment, GaBi, and biodiversity. I also want to thank the other colleagues in the LCM team for their uplifting words during the challenging moments. Special thanks to Ulrika Palme, my supervisor and examiner at Chalmers, for her invaluable feedback and for navigating the biodiversity jungle with me.

I want to thank Anton Forsberg, who continuously and tirelessly listened and supported me throughout the thesis, from thesis topic discussions to the final presentation layout. Clara Heldtander and Julia Gutke, thank you for being people to turn to with thoughts and questions. Lastly, immense gratitude to all my friends and family for bringing joy and unwavering support throughout this thesis and my years at Chalmers.

Stina Dellås, Gothenburg, February 2024

List of Acronyms

Below is the list of acronyms that have been used throughout this thesis:

CF	Characterization factor
C&B	Chaudhary and Brooks
c-SAR	Countryside Species-Area Relationship
ECA	Equivalent Connected area
EU	European Union
GEP	Global Extinction Probability
HF	Habitat Fragmentation
IPBES	The Intergovernmental Science-Policy Platform on Biodiversity and Ecosystem Services
IFOAM	The International Federation of Organic Agriculture Movements
LCA	Life Cycle Assessment
LCI	Life Cycle Inventory
LCIA	Life Cycle Impact Assessment
NCP	Nature's contribution to people
PDF	Potentially Disappeared Fraction of Species
RER	Europe
RoW	Rest of World
SAR	Species-Area Relationship
SHR	Species-Habitat Relationship
USDA	United Stated Department of Agriculture
VS	Vulnerability score

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1
Introduction

1.1 Background

The Convention on Biological Diversity describes biological diversity as "the variability among living organisms from all sources including, inter alia, terrestrial, marine, and other aquatic ecosystems and the ecological complexes of which they are part; this includes diversity within species, between species, and of ecosystems." (“Convention on Biological Diversity”, 2006) Following anthropogenic activities, the functioning and well-being of nature’s ecosystems are declining. According to the Intergovernmental Science-Poilicy Platform on Biodiversity and Ecosystem Services (IBPES) (2019), nature’s ecosystems have decreased by 47%, and around 25% of species are threatened with extinction since prehistory.

The acknowledgment of human impact on ecosystems underscores the importance of national commitments to safeguard biodiversity. The European Unions’s (EU) Biodiversity strategy aims to restore European biodiversity by 2030, and in December 2022, 156 countries pledged to protect biodiversity at COP15 through the Kunming-Montreal Global Diversity Framework. (“Biodiversity strategy for 2030”, n.d.; Lorz, 2023). These commitments emphasize the need for integrating biodiversity into public and corporate decision-making. They urge businesses and financial institutions to assess, monitor, and disclose their effects on biodiversity, fostering awareness, mitigation, and responsible consumption. Given these commitments, there is a clear need for well-developed and established models and indicators for biodiversity (Crenna et al., 2020; Damiani et al., 2023).

The textile industry depends heavily on biodiversity, particularly for raw material production. In 2022, about one-third of textile fibers originated from agriculture and forests (Exchange, 2023). Cotton, the most common natural fiber, ranks second in textile production after polyester, comprising approximately 24% of produced fibers and utilizing 2.4% of global arable land (Granskog et al., 2020). Conventional cotton cultivation negatively impacts biodiversity through extensive water, land, and chemical usage (Delate et al., 2021). Alternative practices like organic production aim to mitigate these impacts by employing less harmful methods integrating the natural ecosystem (Goyal & Parashar, 2023). The ability to accurately quantify biodiversity impacts from fiber production using various cultivation techniques marks a step toward a more transparent textile supply chain and increased consumer awareness.

The urgency of quantifying impacts on biodiversity following textile fiber production and ensuring models that representatively reflect damages to ecosystems set the context of this thesis. Additionally, the Swedish Environmental Research Institute IVL is involved in several projects researching and improving quantification methodology for bio-based systems and industries, including the textile industry. One of the projects is an EU-funded project, Calimero (Calimero, 2022). The results of this study would help the Calimero project to analyze and develop models for biodiversity quantification.

1.2 Aim

This study aims to map the life cycle of conventional and organic cotton fibers and assess their impacts on biodiversity. The intended outcome is to understand cotton fiber production, the related impacts on biodiversity, and how these differ between conventional and organic cotton. Furthermore, it will use three different LCA models to quantify the impacts. It will, therefore, serve as a trial to examine how the models differ and how they translate biodiversity impacts in cotton fiber production.

To concretize the aim of the study, the following research questions will be examined:

- What are the hotspots in the cotton textile production system in terms of impacts on biodiversity?
- How does the production of organic cotton differ from that of the conventional in terms of impacts on biodiversity?
- What aspects of the models are important to capture biodiversity impacts in organic and conventional cultivation processes, and how might they be lacking?

1.2.1 Delimitations

The report will focus solely on the production of cotton fibers and not the further production, usage, and waste management of cotton textiles. It will focus primarily on the effects on biodiversity and ecosystem quality, therefore not considering the impacts on human health, resource availability, etc. It will not consider the economic and social aspects of sustainability. Further delimitations and assumptions made in the study are presented in sections 3 and 4.

2

Theory

The following chapter presents the theoretical framing of the study. It commences with the concept of biodiversity, followed by the process of LCA and biodiversity in LCA. After that, the models used in the study are presented, followed by a description of cotton and cotton cultivation practices.

2.1 Biodiversity

Biological diversity includes all the living things that make up an area. It is commonly divided into several levels and attributes. One widely referred description of the levels of biodiversity is one developed by Noss et al. (1990), presented in figure 2.1. It includes four levels: genetic, species, community/ecosystem, and landscape. The landscape level means the spatial complexity of multiple communities/ecosystems and their interactions in a mosaic landscape (NOSS, 1990). Community/ecosystem refers to the species living in a reasonably homogenous area or ecosystem and the relation between them. Species level refers to examining a specific species in total or a limited area. Finally, the genetic level refers to internal attributes and changes within a species.

	COMPOSITION	STRUCTURE	FUNCTION
Landscape	Identity, distribution, and proportions of patch (habitat) types	Heterogenetity; connectivity; patchiness; fragmentation	Nutrient cycling rates; disturbance processes and retun interval; energy flow
Community/ Ecosystems	Richness; evenness; plant species ratios; dominance diversity curves	Slope and aspects; foliage density; canopy openness; water availability	Productivity; herbivory and predation rates; colonization rate
Species	Absolute or relative abundanace; biomass; density	Dispersion; range; population structure (age and sex rations)	Population fluctuations; phenology; fertility; recruitment rate
Genetic	Allelic diversity; deterious recessives; karyotypic variants	Effective population size; heterozygosity	Inbreeding depression; gene flow; rate of genetic drift

Figure 2.1: The levels and attributes of biodiversity adapted from Knight et al. (2020).

The four levels of biodiversity are divided into three attributes: composition, structure, and function (see figure 2.1). Composition refers to the assortment and diversity of elements encompassing species and genetic diversity; structure includes the tangible organization and configuration of the system, and function includes ecological and evolutionary mechanisms such as gene disturbances and nutrient cycles. This framework is a way to highlight and incorporate the interconnectedness between the different levels and attributes of biodiversity, making sure to capture better the complexity and multifaceted structure of nature (NOSS, 1990).

Anthropogenic activities heavily affect biodiversity, both directly and indirectly. The five primary direct drivers of biodiversity loss, as identified by IPBES (2019), include changes in land and sea use, direct exploitation of organisms, climate change, pollution, and invasion of alien species. Land and sea use changes arise from the destruction, fragmentation, and alteration of natural habitats due to various human activities. Direct exploitation refers to unsustainable harvesting, overfishing, and hunting of species, resulting in population decreases and potential extinction. Climate change alters habitats and ecological processes through temperature increases, leading to sea-level rise, extreme weather, altering precipitation, etc. Anthropogenic pollution from various industrial, agricultural, and urban sources threatens ecosystems, impacting species' survival, reproduction, and health. Additionally, introducing invasive species to the ecosystem can disrupt the balance and outcompete or infect native species, resulting in declining natural biodiversity.

The five major direct drivers of biodiversity loss come from many underlying indirect factors relating to societal values and behaviors (IPBES, 2019). The IPBES 2019 established several categories of indirect biodiversity drivers: economic and technological, institutions and governance, conflicts and epidemics, and demographic and socio-cultural. Economy and technology relate to, e.g., our economic incentives favoring economic growth rather than the conservation and protection of nature and ecosystems. Governance is how institutions, both locally and internationally, impact nature and ensure a truthful valuation of nature's value to humans. Demography includes e.g., population size, urbanization, appreciation of indigenous and local knowledge, and migration as both a cause and effect of environmental degradation. This also relates to how we value and conceive nature and biodiversity.

Biodiversity can be valued in many different ways, both intrinsic, its value in itself, and instrumental, based on what it can provide to humans. The instrumental values are often described as nature's contributions to people (NCP)(Díaz et al., 2018; IPBES, 2022). This concept builds on the ecosystem services described by the Millennium Ecosystem Assessment (MEA, 2005). Diaz et al. (2018) describes them as "all the contributions, both positive and negative, of living nature (diversity of organisms, ecosystems, and their associated ecological and evolutionary processes) to people's quality of life."

Within the generalized description of NCPs, 18 categories of NCPs are organized into three groups: material contributions, non-material contributions, and regulating contributions (Díaz et al., 2018). Material contributions include items, substances, or natural elements, e.g., food, energy, or materials for shelter, clothes, or decoration, directly supporting human physical existence and possessions. Non-material contributions include the influence of nature on psychological or subjective elements supporting individual or collective quality of life. Lastly, regulating contributions include the underlying functional and structural aspects of organisms and ecosystems that modify environmental conditions and the regulating and generating of materials (Díaz et al., 2018).

2.2 Life Cycle Assessment

LCA is a method used to analyze the environmental impact of a product or service considering the entire life cycle (Baumann & Tillman, 2004). It is a tool that provides a systematic way to synthesize the environmental effects (M. A. Curran, 2014). It can be used for many different things, including product development, policy making, and marketing, to name a few. The LCA methodology is described in four parts: goal and scope definition, inventory analysis, impact assessment, and interpretation, presented in figure 2.2.

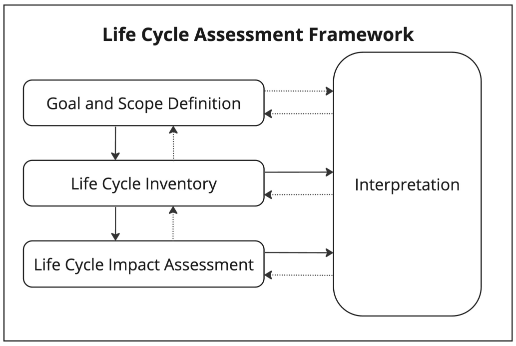


Figure 2.2: A visualisation of the LCA model adapted from Baumann & Tillman (2004)

The first part of the LCA is the goal and scope definition that includes deciding on the product system and purpose of the study (Baumann & Tillman, 2004). The Life Cycle Inventory (LCI) is the second phase of the LCA. It consists of constructing a flow chart including all the processes and flows within and across the system boundaries and collecting data for these processes. The subsequent Life Cycle Impact Assessment (LCIA) evaluates and quantifies the environmental impacts of a product or system by translating its flows into contributions to selected impact categories using characterization factors (CF) (Hauschild & Huijbregts, 2015). The aggregation is based on the inventory analysis and a chosen LCIA model. There are several LCIA models to be used that have different levels of aggregation and different environmental impacts. Finally, the results are interpreted; this phase aims to discuss the ecological performance of the system, identify critical processes, recognize possible interpretations that could improve the sustainability of the system as well, and discuss the uncertainties and limitations of the study following data sources, value choices, etc. (Jolliet et al., 2015).

2.3 Biodiversity in Life Cycle Assessment

Achieving sustainable production and consumption requires acknowledging and assessing these industrial systems' impacts on biodiversity. LCA is a systematic method for environmental impact assessment of products and services that covers various impacts. However, implementing factors related to biodiversity loss is not often overlooked due to a lack of suitable methodology (Lindner et al., 2019). Although the development of models quantifying biodiversity impacts in LCA has been ongoing for over 20 years, no model has yet to sufficiently and comprehensively assess biodiversity pressures and impacts (Winter et al., 2017). Most attempts have been made to incorporate land use impacts in LCA.

A significant challenge is covering the multidimensional nature of biodiversity, including the multiple levels as well as the structure, composition, and function as mentioned in the section 2.1 and figure 2.1 (M. Curran et al., 2016). As for now, the majority of LCIA models developed are mainly focused on species diversity, some on ecosystem diversity, and less on genetic diversity (Winter et al., 2017). The species diversity aims to cover the global, human-driven species extinction (Marques et al., 2021). However, using species loss as the sole indicator of biodiversity risks unfair simplification of the magnitude and interlinkage of ecosystems and biodiversity (Lindner et al., 2019). Subsequently, a broader view of biodiversity is needed to acknowledge ecosystems' current function, resilience, and stability in the long term (Vrasdonk, 2020). Several sources discussing biodiversity representation in LCA mention the need to consider the multifunctionality of ecosystems(Damiani et al., 2023; Gabel et al., 2016; Marques et al., 2021). Ecosystem multifunctionality covers the function of several ecosystem processes supported by local biodiversity, incorporating factors such as abundance (productivity, species diversity) and resilience.

A second challenge with the covering of biodiversity pressures in LCA is the uneven coverage of the main drivers of biodiversity loss as presented by the IBPES (2019) (see section 2.1) (Winter et al., 2017). Climate change, loss of habitat, and pollution are to some extent covered in LCA through such impact categories as land use, water use, greenhouse gas emissions, acidification, eutrophication, and ecotoxicity (Damiani et al., 2023; Winter et al., 2017). Some pressures on biodiversity not covered in LCA include ionizing radiation, electromagnetic radiation, noise, light and odor pollution, poaching, overfishing, monocultural agriculture, and invasive species. These pressures are not included because of reasons such as low data availability and limited knowledge of the impacts on biodiversity (Winter et al., 2017).

Lastly, to ensure acceptance and applicability, there are certain model requirements from LCA developers and practitioners. LCA is a valuable tool that aggregates environmental impacts. However, it is time-consuming, especially in the data collection. Therefore, models developed to be applied in LCA should consider the data collecting and ensure that the data is possible to acquire, reliable, and can be found with limited effort (Lindner et al., 2019). Furthermore, the output of the models should be aggregated and easy to understand and communicate to stakeholders to ensure usability.

2.3.1 Land Use

Two different types of land use are generally considered in life cycle inventories: land transformation and land occupation (Koellner et al., 2013; Vrasdonk, 2020). Land occupation (also referred to as land use (LU) relates to the land being used in the intended productive way and is kept as such, postponing the return to a natural or semi-natural state. Land transformation (also referred to as land use change (LUC)), the characteristics and properties of a piece of land alter, either from a natural or min use phase, to suit the intended use, e.g., agriculture, and the impacts on the land quality after a time of regeneration. Figure 2.3 visualizes these impacts.

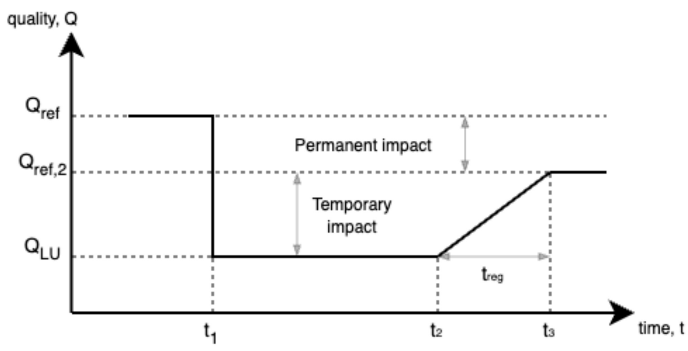


Figure 2.3: Quantification of land use impacts over time, adapted from (Koellner et al., 2013; Lindner et al., 2019; Vrasdonk et al., 2019).

Land occupation and transformation broadly impact the land's ecosystem quality, denoted as Q on the y-axis. This value reflects the ability of an ecosystem or several ecosystems on a landscape scale to keep biodiversity and deliver services valuable to humans (Koellner et al., 2013). Q_{ref} represents the reference state of the land, an essential parameter in land use modeling (i Canals & de Baan, 2015). It is the benchmark state against which the current land state is assessed. Typically, the Potential Natural Vegetation (PNV) is employed as a reference state, indicating the expected condition of natural vegetation in the absence of human activities (Koellner et al., 2013). However, the appropriate reference state to use in LCA is widely discussed. Koellner et al. (2013) suggest alternative reference states, such as the current or natural mix of the landscape, and Vrasdonk et al. (2019) propose reconsidering the reference state in LCA to align with conservation practices and policies, emphasizing the sustainable coexistence of natural and anthropogenic ecosystems.

Looking again at figure 2.3, the anthropogenic land use interventions decrease the land quality to Q_LU. The second important factor reached now is the regeneration time t_{reg} used to quantify the transformation impacts. This time frame depends on factors such as the degree of impact, the specific land use, and geographical conditions in the area (i Canals & de Baan, 2015). Regeneration time is inherently uncertain and dependent on the impact pathway considered. The assumption that the natural state will fully recover is often somewhat unrealistic, so permanent impacts are also to be considered, resulting in the final state of the land being $Q_{ref,2}$ (Lindner et al., 2019).

2.3.2 Species estimations

Several LCIA methods use estimated species richness as a unit of biodiversity loss. A method of estimating species richness is the Species-Area Relationship (SAR). The SAR is an empirically measured pattern and relationship between the size of a habitat and the amount of taxa in it. This pattern can arise from colonizing habitats on islands or patches of land of the loss, reduction, and fragmentation of previous significant habitats. (Lindqvist et al., 2016). The most commonly used one is a power model presented in question 2.1.

$$S = C * A^z \tag{2.1}$$

In the given equation, S denotes the number of taxa, A represents the area of the land, c is the taxonomic group and region-specific proportionality presenting lowest number of species in one sample plot and z describes the rate of which the species-area curve decelerates (Lindqvist et al., 2016; Proença & Pereira, 2013; Tjørve & Tjørve, 2017). Although widely used, this power model has been criticized for its tendency to overestimate and oversimplify extinction rates. Notably, it overlooks the diversity of habitats, meaning the species richness found in multi-habitat landscapes (Proença & Pereira, 2013). Additionally, it assumes that all natural areas dominated by humans are unlivable for the species in that area, disregarding their response to changes in habitat and species partial or total tolerance to human-modified areas (Pereira et al., 2014). To address these limitations, variations of the SAR have been developed to align better with reality. Some of these SAR variants are used in the LCIA models considered in this study, and the various developments are described in the model descriptions.

2.4 ReCiPe2016

ReCiPe2016 is an operational LCIA model developed in the early 2000s that provides 18 mid- and three end-point categories to assess environmental impacts (Goedkoop et al., 2009; Sanyé-Mengual et al., 2022). It offers globally harmonized characterization factors aggregating end-point impacts into three primary areas: human health, natural environment, and resource scarcity (Huijbregts et al., 2017). Figure 2.4 provides an overview of the impact categories utilized in ReCiPe2016 (Huijbregts et al., 2017).

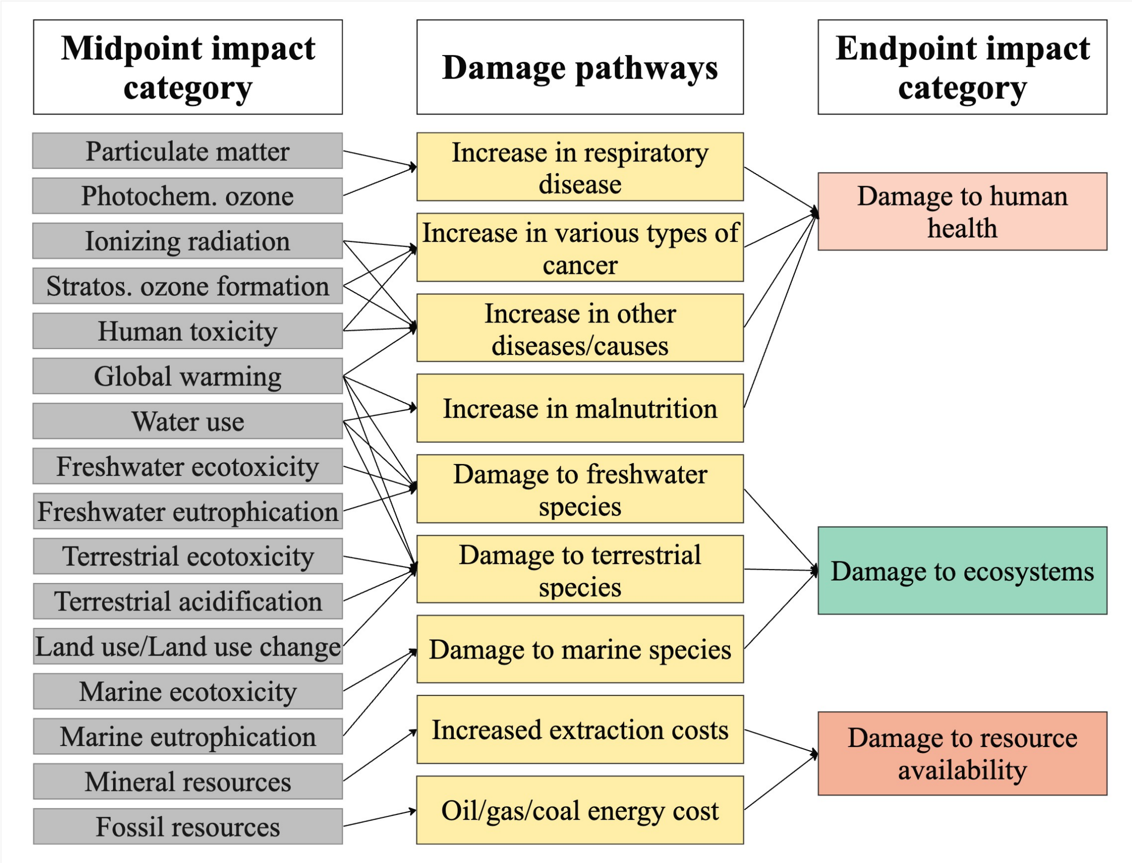


Figure 2.4: Overview of the impact categories covered in ReCiPe2016 adapted from Huijbregts et al. (2017).

The model utilizes LCI data, converting these values to midpoint impact categories. The midpoint CFs present the strength of the emission as an amount of a given reference substance (Huijbregts et al., 2017). For example, emissions contributing to global warming potential are measured in kg CO_2 equivalents. End-point categories indicate the harm caused by a stressor after the cause-effect sequence. The calculation from midpoint to end-point is based on the equation 2.2 below. For a complete description of all impact pathways and calculations used in the model, please refer to the model description "ReCiPe 2016 v1.1: A harmonized LCIA method at midpoint and end-point level" provided by Huijbregts et al. (2017).

$$CF_{e_{x,c,a}} = CF_{_{x,c}} * F_{M->E,c,a} \tag{2.2}$$

In the equations, the index a is the area of protection referring to one of the three end-point categories, the index x is the stressor of concern, meaning the resource used or the emissions released, and the factor $F_{M->E,c,a}$ is the mid- to end-point conversion factor (Huijbregts et al., 2017).

Equation 2.2 also includes a c value, which is named the cultural perspective and handles the uncertainty of the model (Goedkoop et al., 2009). Aggregation and characterization models entail inherent uncertainty due to the complex nature of natural processes and climate change mechanisms. ReCiPe2016 has incorporated three value choices to address this uncertainty, grouping assumptions like time horizon, future socio-economic developments, and adaptation potential. The value choices are the individualist perspective, based on short-term interest and technological optimism; the hierarchic perspective, based on scientific consensus concerning impact mechanisms; and the egalitarian perspective, being the most prudent with the most extended time frame. These value choices provide different CFs and the selection of which of the three perspectives to consider is made by the LCA practitioner based on the intended goal and scope. A further description of the value choices and how they are interpreted in every impact category can be found in the model description by Huijbregts et al. (2017).

2.4.1 Biodiversity and Land Use in ReCiPe2016

In ReCiPe2016, biodiversity impacts are addressed under the "Damage to Ecosystems" end-point category (visualized in figure 2.4), incorporating cause-and-effect chains outlining potential damage to terrestrial, freshwater, and marine ecosystems (Huijbregts et al., 2017). They are given in a value of species.yr, translating to the impact on species richness following an impact. The "reversible or irreversible disappearance of a species or stress on a species in a certain region during a certain time" as described in the model description of the first iteration of the model provided by Goedkoop et al. (2009)

The midpoint impact categories, as given, are measured in "potentially disappeared fraction of species" (PDF) following the substance emitted, a value measuring the relative species richness following an impact. To obtain the final end-point value in species.yr, the PDF value, representing the midpoint category and specific impact-related factors, is multiplied by the global average species density for terrestrial, freshwater, and marine species.

Land use in the ReCiPe2016 model covers land transformation, occupation, and regeneration processes, aligning with the quantification described in the previous section, utilizing the reference state PNV. The land use types include used forest, pasture and meadow, annual crops, permanent crops, mosaic agriculture, and artificial areas (industrial, roads, railways, landfills, etc.). The land occupation CFs are determined by the relative species loss based on field data comparing observed species under the specific land use to naturally occurring species in the region (de Baan et al., 2013).

The occupational impact value is multiplied by half the estimated regeneration time to obtain transformation CFs. Regeneration times are based on average passive recovery times developed by Curran et al. (2014), distinguishing between open vegetation (e.g., grassland, shrubland, savanna) and forest. The end-point characterization factor is derived by multiplying the midpoint and a conversion factor, as shown in equation 2.2. The conversion factor is the product of the species density and the relative species loss following annual crops (Goedkoop et al., 2009). This all provides final values in species.yr for land use.

2.5 Chaudhary and Brooks

Chaudhary and Brooks (C&B) is an LCIA model examining and quantifying the potential species loss following land use and land use change and presents the values in the unit PDF (Chaudhary & Brooks, 2018). The model derives regional, global, ecoregion-specific, and country-aggregated CFs from five land-use types under three different intensity levels. The taxonomic groups are mammals, birds, amphibians, plants, and reptiles. Furthermore, it provides these CFs for 804 terrestrial ecoregions based on the map developed by Olsson et al. (2001). As a reference state, they employ the same region's natural, undisturbed ecosystem (Chaudhary et al., 2015). The land occupation CFs are presented in PDF/m^2, and land transformation CFs are expressed in PDF $\cdot$ yr/m^2. A visualization of the model, showing the accounted-for land use types, intensity levels, and taxonomic groups, can be found in figure 2.5.

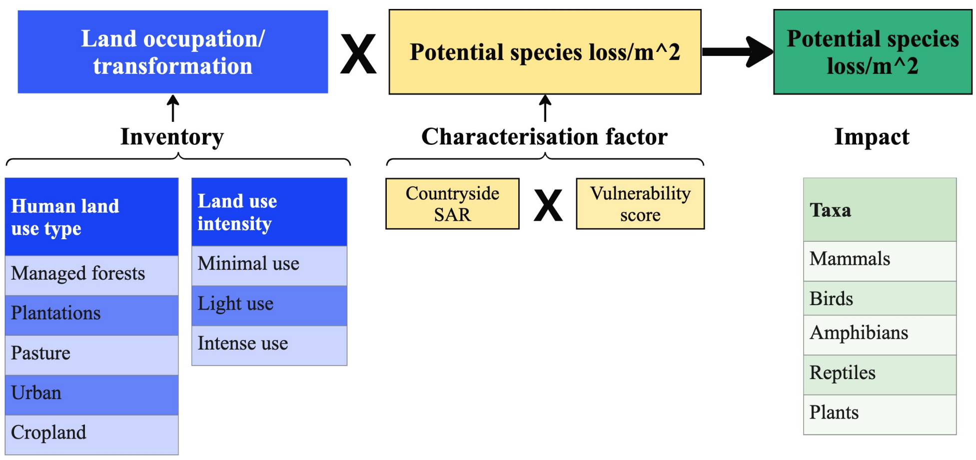


Figure 2.5: Visualization of the C&B land use model as adapted from Chaudhary & Brooks 2018.

The following section describes the derivation of the CFs and the assumptions they are based on. In these equations, the index i indicates land use type (i=1:16), j indicates ecoregion (j=1:804), and g indicates species group (g=1:5).

The model is based on the countryside species-area relationship (c-SAR), a development of the species estimation model SAR described in section 2.3.2 (Chaudhary & Brooks, 2018; Chaudhary et al., 2015). This model includes the variability of habitats present in a landscape and the different ways species reside in them, recognizing that species use habitats that are not native to them (Pereira & Daily, 2006). This is implemented by adding the variable habitat affinity described further in this section. The c-SAR is calculated through equation 2.3 (Chaudhary & Brooks, 2018).

$$S_{loss,g,j} = S_{org,g,j} * \left(1 - \left(\frac{A_{new,j} + \sum_{i=1}^{16} h_{g,I,j} * A_{i,j}}{A_{org,j}}\right)^{z_j}\right) \tag{2.3}$$

This equation calculates the total species loss, $S_{loss,g,j}$, for each species group in the 804 ecoregions. $S_{orgs,g,j}$ represents the total number of species residing in the ecoregion's area in the reference state, a value collected from species databases. $A_{org,j}$ represents the ecoregion's total area, and $A_{new,j}$ is the area of natural habitat in the ecoregion currently. Both these values are derived from available global land use maps. $A_{i,j}$ is the current area of land under land use type i calculated through $A_{i,j} = A_{broad,i,j} * p_{i,j}^{intensity}$, where $A_{broad,i,j}$ is the total area of a particular land use type and $p_{i,j}^{intensity}$ is the proportion of land under every intensity.

In the c-SAR equation 2.3 z_j is the region-specific SAR exponent as explained in section 2.3.2. The variable $h_{g,i,j}$ is the affinity of the taxon g to the land use type i in ecoregion j. The habitat affinity ($0<h_{g,i,j}<1$) is a proxy of the usability of an area or habitat by a taxonomic group. This assumes that a species in its natural habitat has an affinity of 1 (Pereira et al., 2014). It describes the suitability or preference of a particular species for a specific habitat due to its adaptations, requirements, or specialized characteristics. Table 2.1 presents the taxon affinity values for the different land use intensities for cropland averaged over all ecoregions as provided by Chaudhary et al. (2018).

Table 2.1: Average taxon affinity values used in C&B (Chaudhary & Brooks, 2018).

Land use intensity	Mammals	Birds	Amphibians	Reptiles	Plants
Minimal	0.102	0.115	0.127	0.425	0.425
Light	0.076	0.083	0.101	0.299	0.299
Intense	0.071	0.077	0.094	0.279	0.279

Chaudhary & Brooks (2018) mean that one reason for the generally low values of habitat affinity for all three intensity levels is that the most significant impact on species richness in cropland production is the clearing of the natural habitat to make way for the cropland. The intensity levels considered for cropland are described by Chaudhary & Brooks (2018) and presented in table 2.2.

Table 2.2: The description of the different intensity levels considered in C&B. (Chaudhary & Brooks, 2018)

Intensity level	Description
Minimal use	Low-intensity farms: small fields, mixed crops, crop rotation. Little or no inorganic fertilizer use, pesticide use, plowing, irrigation, and mechanization.
Light use	Medium intensity farming: some but not many of the following: large fields, annual plowing, inorganic fertilizer application, pesticide application, irrigation, no crop rotation, mechanization, monoculture crop.
Intense use	High-intensity monoculture farming: large fields, annual plowing, inorganic fertilizer application, pesticide application, irrigation, mechanization, no crop rotation

Moving on, the total projected species loss is allocated to a specific land use type by multiplying the total species loss in an ecoregion $S_{loss,g,j}$, calculated through equation 2.3, with an allocation factor $a_{i,j}$.

$$S_{loss,g,i,j} = S_{loss,g,j} * a_{i,j} \tag{2.4}$$

The allocation factor depends on the value change in habitat affinity $(1 - h_{g,i,j})$ of a specific taxon under one particular land use type and the area of the land use type $A_{i,j}$ over the sum of the same value for all taxon as presented in equation 2.5. It has a value of between 0 and 1, and the sum of all allocation factors over all the land use types in a region is 1.

$$a_{i,j} = \frac{A_{i,j}(1 - h_{g,i,j})}{\sum(A_{i,j}(1 - h_{g,i,j})} \tag{2.5}$$

To acquire the regional CFs, the value $S_{loss,g,i,j}$ is divided by the current area of land use type i as presented in equation 2.6.

$$CF_{reg,occ,g,i,j} = \frac{S_{loss,g,j} * a_{i,j}}{A_{i,j}} = \frac{S_{loss,g,i,j}}{A_{i,j}} \tag{2.6}$$

Compared to land occupation CFs, the land transformation CFs additionally account for the regeneration time of the species group g in region j and land type i. The $CF_{reg,occ,g,i,j}$ is the CF for land occupation. The land transformation CFs are calculated by multiplying half the biodiversity regeneration time (Chaudhary & Brooks, 2018).

$$CF_{trans} = CF_{occ} * 0.5t_{regen} \tag{2.7}$$

Then, global CFs are finally obtained through the multiplication of the $CF_{reg,occ,g,i,j}$ with the vulnerability score

$$CF_{glo,g,i,j} = CF_{reg,g,i,j} * VS_{g,j} \tag{2.8}$$

The vulnerability score (VS) is a value between 0 and 1 and denotes the proportion of the species range size within an ecoregion weighted by their extinction risk(Chaudhary & Brooks, 2018). For example, a vulnerability score of 1 occurs if all species within an ecoregion are critically endangered and their only range is within the studied ecoregion. For further description of the model, please refer to the model article "Land Use Intensity-Specific Global Characterization Factors to Assess Product Biodiversity Footprints" by Chaudhary and Brooks (2018).

2.6 Habitat Fragmentation Model

The habitat fragmentation (HF) model, developed by Kuipers et al. (2021), considers the impacts of land use change, including the combined effects of habitat conversion and fragmentation. It presents CF for land occupation and transformation considering 702 terrestrial ecoregions (based on the map by Olsson et al. (2001)), four land use types (urban, cropland, pasture, and forestry), and four taxonomic groups (mammals, amphibians, birds, and reptiles). Similar to the C&B impact model, it uses species richness as the final indicator and presents the impact in the unit PDF. They use a reference state described as the land absent of anthropogenic land use (Kuipers et al., 2021).

Throughout the upcoming description of the model, certain indexes will be used to denote certain variables where g (1:4) is species group, j is ecoregion (1:702), and i (1:4) is land use types.

The model builds on the species-habitat relationship (SHR), which is a development of the c-SAR model used in C&B (equation 2.3) with the incorporation of the equivalent connected area (ECA) concept (Kuipers et al., 2021). The ECA measures effectively connected habitats by considering dispersal distances and species permeability. It is developed by comparing the current state of habitat connectivity with the natural reference state. ECA serves as a metric to assess the connectivity of the landscape, representing the current habitat pattern's effectiveness in supporting ecological connectivity by comparing the connectivity of the existing habitat pattern to that of a hypothetical, maximally connected habitat patch of a specific size (Saura et al., 2011). This develops a model that considers species richness resulting from land conversion, varying suitability, and land connectivity. The SHR model is as follows:

$$PDF_{g,j,reg} = 1 - \left(\frac{H_{g,j}}{H_{g,j,ref}}\right)^{z_{g,j}} = 1 - \left(\frac{\sum_i h_{g,j,i} * ECA_{g,j,i}}{\sum_i h_{g,j,i} * ECA_{g,j,i,ref}}\right)^{z_{g,j}} \tag{2.9}$$

This equation calculates the regional PDF for taxonomic group g and region j, $PDF_{g,j,reg}$. $H_{g,j}$ in the equation is the suitable connected habitat. It is the product of the habitat suitability or habitat affinity $h_{g,i,j}$, as described in section 2.5, multiplied with the ECA of land type i for species group g in region j. The ECA is expressed as a unit of area derived from the amount and size of individual patches of land use type and the probability of species dispersal between the different patches (Kuipers et al., 2021).

A summarizing visualization of the parameters and variables in the ECA value is given in figure 2.6. For the full description of the variables and equations, please refer to "Considering habitat conversion and fragmentation in characterization factors for land-use impacts on vertebrate species richness" by Kuipers et al. (2021).

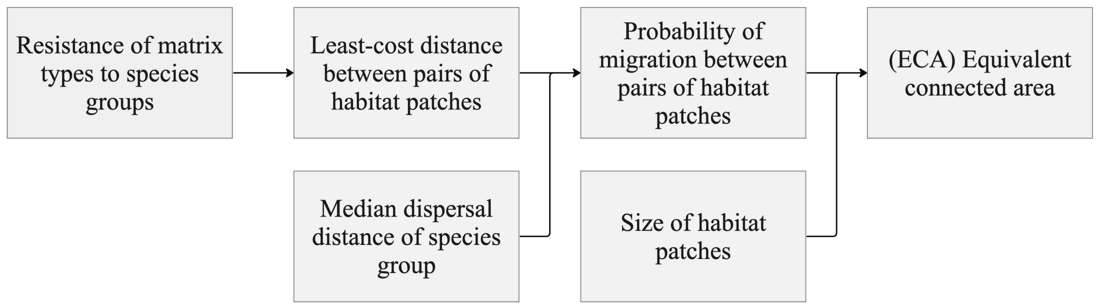


Figure 2.6: A visualization of the equivalent connected area (ECA) parameters. Adapted from Kuipers et al. (2021)

The PDF (equation 2.9) is multiplied by the taxonomy and region-specific global extinction probability (GEP) value to acquire a global and vulnerable scope to the CF. This variable highlights the contribution that regional species loss might have on global extinctions. The CFs are provided as both marginal and average. The average occupational characterization factor is calculated.

$$CF_{g,i,j,occ,avg} = PDF_{g,j} * A_{lu,j}^{-1} * q_{g,i,j} \tag{2.10}$$

The $PDF_{g,j}$ is the impact calculated through 2.9, A is the total area of all types of land use combined, and q is the distribution factor. The distribution factor depends on the area and the habitat affinity $h_{g,i,j}$. Similar to the transformation CFs in C&B, the transformation CFs are calculated by multiplying the occupation CFs with half the value of the regeneration time.

$$CF_{g,i,j,trans,avg} = CF_{g,i,j,occ,avg} * 0.5t_{regen} \tag{2.11}$$

For further description of the model, please refer to "Considering habitat conversion and fragmentation in characterization factors for land-use impacts on vertebrate species richness" by Kuipers et al. (2021).

2.7 Cotton fiber production

The use of cotton fiber can be traced back to India and the Middle East around 5000 BC (Goyal & Parashar, 2023). Cotton's many beneficial characteristics, including comfortability, durability, and absorption, have made it a popular fiber for textile production and contributed to its large-scale distribution and proliferation worldwide. It is native to tropical and subtropical regions but is grown in many climates and soils (Baydar et al., 2015). The major cotton-producing countries as of 2022 were China, India, USA, Brazil, Australia, and Turkey, according to the United States Department of Agriculture (USDA) (2023a). There are several genetic varieties of cotton, including the four major commercialized ones: Gossypium hirsutum (American cotton), Gossypium barbadense (Egyptian cotton) and Gossypium arboreum and Gossypium herbaceum (Asian cotton). Gossypium hirsutum accounts for about 90% of global cotton production (Gupta & Gupta, 2023).

Cotton is a perennial plant that has been bred and domesticated to be grown as an annual plant, planted and harvested every year (Meshram et al., 2022). The production of cotton textiles commences with cultivation, harvesting, and ginning processes. Cultivation involves field preparation and management practices like fertilization, pest control, and irrigation, typical of agricultural activities. Subsequently, cotton is harvested, which varies globally, ranging from manual harvesting to fully mechanized techniques (Dadgar, 2020). Cotton ginning entails the separation of cotton lint fibers from the seed and the removal of additional impurities. The cotton seeds comprise around half of the cotton (Munir et al., 2020). While considered a byproduct of cotton cultivation, the seed plays a vital role worldwide, being utilized for both cottonseed oil in cooking and as animal feed.

Conventional cotton is known for being one of the most chemical- and water-intensive crops cultivated today and utilize 2.4% of the world's arable land (Delate et al., 2021; Granskog et al., 2020; Kazan et al., 2020; Venkatesan & Periyasamy, 2019). These cultivation practices lead to severe environmental damage. Water use affects local freshwater resources; toxic chemicals pollute local ecosystems and drinking water and decrease soil quality; land use impacts ecosystems and biodiversity (Exchange, 2023; Gupta & Gupta, 2023).

2.7.1 Organic Cotton

The International Federation of Organic Agriculture Movements IFOAM describes organic agriculture as "a production system that sustains the health of soils, ecosystems, and people. It relies on ecological processes, biodiversity, and cycles adapted to local conditions rather than using inputs with adverse effects. Organic agriculture combines tradition, innovation, and science to benefit the shared environment and promote fair relationships and good quality of life for all involved" (Paull, 2010). It is closely linked to agroecology, a comprehensive approach to sustainable agriculture and food systems that integrates ecological and social principles to optimize interactions between plants, animals, humans, and the environment while promoting socially equitable food and agricultural systems (FAO, 2024).

Organic cotton, representing only 1% of global cotton cultivation, refers to cotton cultivated according to standards for organic farming (Goyal & Parashar, 2023; Mageshwaran et al., 2019). It includes cotton cultivated without agrochemicals such as chemical fertilizers, pesticides, growth regulators, and defoliants. Some primary practices in organic farming of cotton include crop rotation with legumes, recycling of crop residue, application of farmyard manure, incorporating multiple crops in the same area (intercropping), and appropriate water management, to name a few (Mageshwaran et al., 2019). However, this can be maintained in different ways globally.

Organic agricultural practices have been shown to reduce GHG emissions, improve soil health, and increase biodiversity multifunctionality, amongst others (Ricciardi et al., 2021; Wittwer et al., 2021; Yang et al., 2024). Van der Werf et al. (2020) argue for the need to cover better these attributes and others within the scope of LCA. This includes assessing soil and cropland degradation, biodiversity, and impacts from pesticide use with the best available models and methods. Furthermore, it is important to consider climatic and regional ecosystem characteristics and specific agricultural practices in detail to ensure proper coverage of these attributes.

One more consideration given by van der Werf et al. (2020) is to use both product-based and area-based functional units in LCA. This is to provide a fair and multi-dimensional analysis of organic cultivation based on one commonly referred controversy regarding organic cotton and agricultural systems. It is the yield gap and crop productivity difference. The yield gap between conventional and organic agriculture is varied and contextual. Seufert et al. (2012) conducted a literature search and concluded that organic cotton yields are generally lower but can vary between 5-34% between conventional and organic agriculture. De la Cruz et al. (2023) concluded in their analysis of organic and conventional yield gap over different climate types that organic yield generally is 18.4% lower but is challenging to estimate due to temperature and precipitation variations. Finally, Riccardi et al. (Ricciardi et al., 2021) claim that higher yields can be found on smaller-scale farms.

Furthermore, some organic cultivation aims to develop practices of land sharing. Land sharing is a cultivation process where little land is set aside for conservation, and less intense techniques are performed to maintain biodiversity throughout the agricultural land (Fischer et al., 2014). This is opposed to land sparing, where more land is set aside for conservation, and the other land is intensively cultivated to produce human output.

3
Methods

The following chapter describes the methods used in the study. Life cycle assessment (LCA) was the core method of the project. Apart from that, a literature study is carried out. These separate parts of the process are described below in sections 3.1 and 3.2.

3.1 Literature Study

A literature study is a method to find and summarize previous research on a topic to create a foundation for theory, research, and method development (Snyder, 2019). The study aimed to examine the state of the art of quantifying biodiversity loss in LCA and acquire knowledge of the current research on cotton production systems, biodiversity, and LCA. This was done by researching Google Scholar, Science Direct, and Scopus databases. The words and phrases used to search for relevant primary articles were life cycle impact assessment, cotton production/cultivation, cotton industry, biodiversity, and methods/models of quantifying biodiversity loss. Additional information was provided through discussions with experts and researchers in the field.

3.2 LCA

The second part of the method was an LCA comparing the two different product systems, conventional and organic cotton cultivation. It aimed to examine and analyze the systems' impacts on biodiversity and how they differ. Additionally, it aimed to analyze how the different models quantify the impacts to conclude essential aspects needed in LCIA for conventional and organic farming. This systematic method was chosen due to the aim and intent to analyze the entire product system within the set system boundaries. Additionally, since the LCA method is based on the system's function, this allowed for comparing product systems (Baumann & Tillman, 2004).

Many models used for biodiversity quantification are made to be applied within the impact assessment of LCA, so for that reason, LCA was a relevant tool. The LCIA was carried out by three models: ReCiPe2016, an operational model covering multiple impact categories, and two non-operational models specifically examining biodiversity impacts of land use, C&B, and HF. These models are all explained and described in sections 2.4, 2.5, and 2.6.

The calculation of the LCIA was carried out in the LCA software GaBi for the ReCiPe2016 model, and the visualization of the results and allocation was done in Excel. For the C&B and HF, the entire calculations were done in Excel through data provided by the developers of these models (Chaudhary & Brooks, 2018; Kuipers et al., 2021). The full LCA is presented in chapter 4.

4
Life Cycle Assessment

The following chapter will present the LCA, including the goal and scope, the life cycle inventory, and the LCIA.

4.1 Goal and Scope

This section will present the goal and scope of the LCA performed.

4.1.1 Goal and Purpose of the study

The LCA aimed to assess the biodiversity impacts of the life cycle of conventional and organic cotton fibers. This was done through a comparative, attributional life cycle assessment. The objectives can be summarized into two primary aspects. Firstly, it aimed to acquire an understanding of cotton fiber production, the related impacts on biodiversity, hotspots in production, and how these differ between conventional and organic cotton. Secondly, it was a trial study to see how well the three LCIA models can be applied to textile fiber production and how these translate the differences between conventional and organic cotton production. Hence, the study results can be relevant in two main applications. Firstly, it gives some insight into conventional and organic cotton cultivation and its impact on biodiversity, relevant for stakeholders within the textile fiber industry. Secondly, the results are relevant for LCA researchers intending to develop models used for biodiversity quantification.

4.1.2 Scope of the study

The following section describes the scope of the LCA, including the functional unit, the system specifications, assumptions, allocation procedures, and the selection of LCIA models and impact categories. The system in question was the cultivation of cotton fiber.

4.1.2.1 Functional unit

The functional unit should reflect the system's function (Baumann & Tillman, 2004). In the case of cotton cultivation and this study, the function of the two systems is to produce cotton fibers. Therefore, the functional unit of the system was set to 1 tonne of cotton fiber. This was translated in the system to the reference flows: 1 tonne of cotton fiber produced with conventional methods and 1 tonne of cotton fiber produced organically. This was chosen to compare the two different systems and provide an understandable functional unit.

4.1.2.2 System Boundaries

The system process is the cultivation of cotton fiber. This includes preparing the field, sowing, and field operations, including irrigation, fertilization and pest control, harvest, transport, and cotton ginning. Figure 4.1 below presents the system in a simple flowchart. The system varies between organic and conventional cotton in terms of several attributes, but this will be explained in section 4.2

The scope of the analysis is set within a cradle-to-gate assessment, from cultivation to gin gate, starting after the harvest of the previous crop. This means that all the steps from resource extraction up to the factory gate of cotton fiber production and all emissions to soil, water, and air are considered. Further applications of the cotton fiber, such as yarn manufacturing, textile manufacturing, use phase, and EoL treatment, will not be considered in this study.

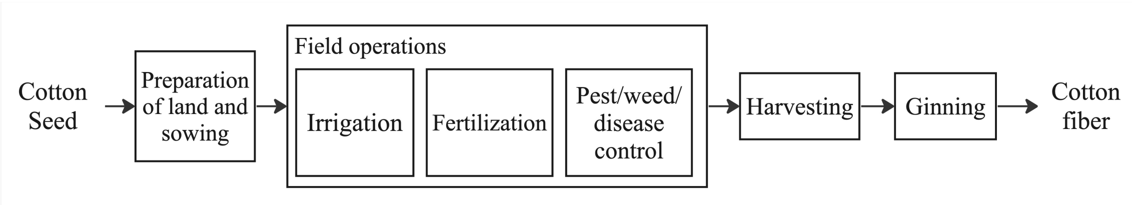


Figure 4.1: Simple flow chart of the cotton cultivation process.

Geographical boundaries The study's geographical boundaries were set within Turkey's national borders for cultivating and ginning cotton fibers and producing auxiliary materials. It must, however, be mentioned that for specific background processes where Turkish data was not found, a European or globally aggregated process was used. This will be further specified in section 4.2.

Technical boundaries Regarding technical boundaries, the construction of capital goods, including storage facilities, construction of ginning facilities and machinery, and construction of agricultural machinery, was excluded. This decision is based on several factors. First of all, proper information on the type of machines and storage used was hard to acquire and fostered data uncertainty, contributing to the decision to exclude these factors. Secondly, the storage facilities as well as the machinery and facilities used in the ginning process, were assumed to be the same for conventional and organic cotton production, meaning that including these would not make a difference in comparing the two systems.

Agricultural machinery construction was assumed to have a comparatively small impact on the production system. This has been proven not necessarily true; Tokede and Rouwette (2024) acknowledge that capital goods can have a relevant impact on the process, especially in factors such as land use toxicity. However, they also discuss that the inconsistency and availability of data create uncertainties in the inclusion. The exclusion of capital goods will be further discussed in chapter 6. An exception to this exclusion of capital goods is where Ecoinvent and GaBi datasets were used since they include capital goods production in their aggregated datasets.

4.1.2.3 Selection of LCIA Models and Impact Categories

The study used three LCIA models: ReCiPe2016, a land use intensity model (C&B), and a land use fragmentation model (HF). ReCiPe2016 was chosen as a widely applied operational method deemed interesting for stakeholders and LCA practitioners. Furthermore, it considers multiple biodiversity impacts of interest to establish the most impactful. Since this LCA and the project aimed to examine the effects on biodiversity and ecosystem quality from cotton cultivation, the study was limited to the "Damage to ecosystems" endpoint factor. Table 4.1 summarizes the mid-point impact categories contributing to the endpoint.

Table 4.1: ReCiPe2016 endpoint CFs per impact category.

Mid-point impact	Unit
Ecosystem quality: Terrestrial	
Climate change	kg CO_2-eq to air
Ecotoxicity	kg 1,4-DCB-eq to industrial soil
Water use	water-eq consumed
Acidification	kg SO_2-eq to air
Photochemical ozone formation	kg NO_x-eq to air
Land use	m^2 × yr annual cropland-eq
Ecosystem quality: Freshwater	
Climate change	kg CO_2-eq to air
Eutrophication	kg P-eq to freshwater
Ecotoxicity	kg 1,4-DCB-eq to freshwater
Water use	m^3 water-eq consumed
Ecosystem quality: Marine	
Ecotoxicity	kg 1,4-DCB-eq to marine water
Eutrophication	kg P-eq to freshwater

The two land-use models, C&B and HF, were chosen because of their relevance in examining land use within cotton cultivation. Land use significantly impacts agricultural systems and substantially contributes to biodiversity loss globally. C&B was selected due to its inclusion of several land use intensity factors relevant to the project due to the comparison of conventional and organic cultivation practices. HF was chosen as it considers the fragmentation effect of land use, a relevant impact on biodiversity following human land use not covered in the other models. Both these models use the endpoint unit PDF.

4.1.2.4 Allocation

The system includes two points of allocation. Firstly, the emissions and upstream systems of manure production are used for the fertilization of organic cultivation.

Manure is initially a waste stream from other systems; therefore, no environmental burden is allocated to it as an input.

Secondly, there is a multi-output process in the system. This is the ginning process where the resulting valuable outputs are cotton fiber and cotton seeds, which are further used in other industries as described in the theory chapter 2.7. As described in the section 2.2, the allocation should, if impossible to avoid, firstly be based on physical attributes and secondly on other attributes such as economic value. According to the gin data provided by Ecoinvent, the weight ratio is nearly 1:2 for fiber and seeds due to the higher weight of the seeds. Consequently, if the allocation were based on weight, about 50% of the impacts would be allocated to the cottonseed. Considering that this would constitute an unfair allocation of the outputs, the economic value is examined. Economic data for cottonseeds and cotton fiber in Turkey was not found; therefore, the economic allocation is based on national data from the United States provided by the USDA. According to the USDA (2022), the five-year average value of cotton fiber from 2018-2022 was 1725$/ton, and the cottonseed was 212$/ton. This results in an allocation of 12% to the cottonseed and 88% to the cottonfiber. Following that, this choice constitutes a more fair allocation based on the reason for the study.

4.1.2.5 Assumptions and Limitations

Several assumptions and limitations are made in the scope of this LCA. Firstly, it is assumed that there are no impacts from land transformation; this was chosen due to the difficulties in acquiring reliable data on timescales of cotton production in Turkey. However, since this impacts the environmental burden of land use, a sensitivity analysis was done to examine the effects of the inclusion. Furthermore, crop rotation and intercropping are not considered in the organic cotton cultivation. These are typical within organic cultivation, but this was excluded due to difficulties in the modeling and the fact that the organic process wasn't based on first-hand data and process. Carbon sequestration was not considered because the carbon sequestration of the cotton plants isn't considered a long-term carbon sink. Soil carbon levels and emissions were additionally not considered due to the uncertainties in the modeling of it.

4.2 Inventory analysis

The following section presents the inventory data, a description of the two systems, and the process flowcharts. The conventional cotton production will first be explained, followed by the organic. No first-hand data was available for the procedures, so they are based on datasets from GaBi and Ecoinvent and literature sources. Datasets from GaBi and Ecoinvent were additionally used for the background processes, including producing pesticides, fertilizers, energy, electricity, diesel, and cottonseeds. These datasets' specific names and sources are provided in Appendix A. Since most processes are based on data supplied by Ecoinvent and GaBi, the numerical values and data specification will often not be provided in the report due to certification and privacy regulation issues. The data will instead be referred to as the Ecoinvent and GaBi datasets used.

4.2.1 Conventional cotton system

The conventional cotton production is presented in the flowchart below (figure 4.2).

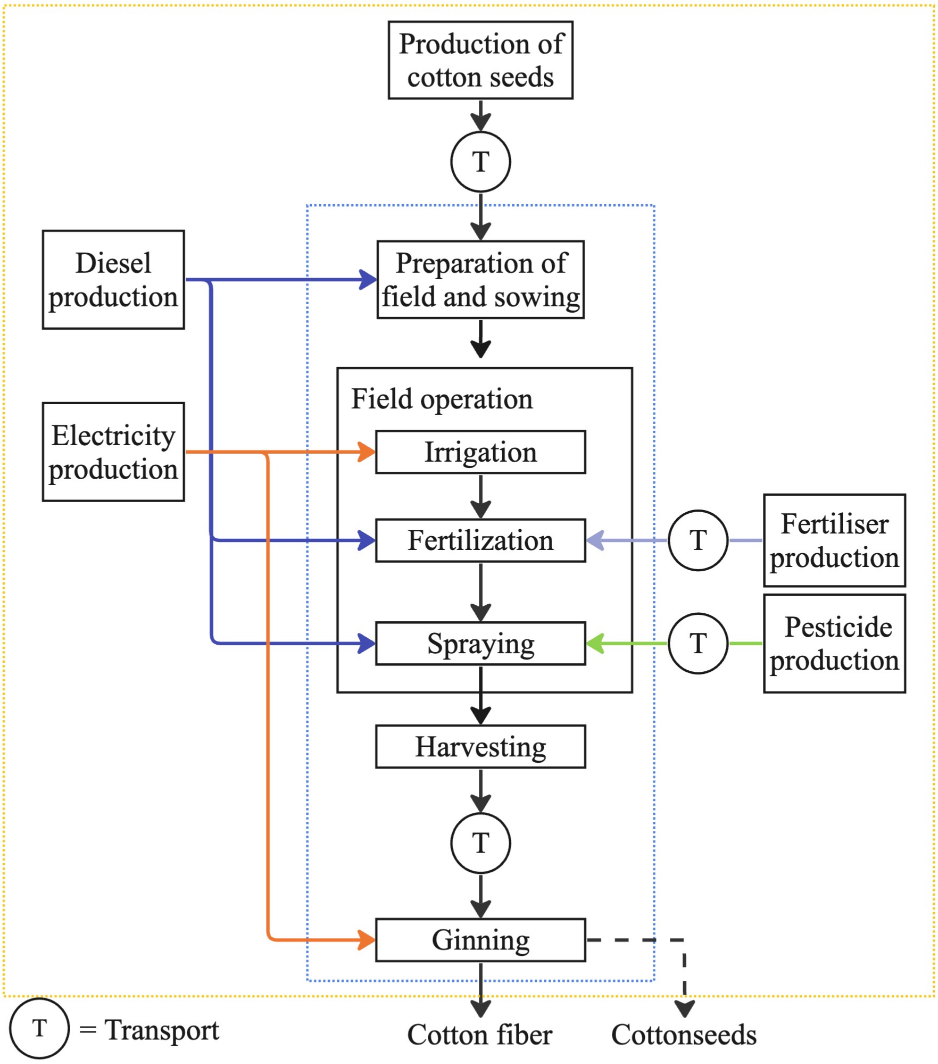


Figure 4.2: Flow chart for the conventional cotton process. The blue box represents the foreground system boundaries, and the yellow box represents the total system boundary, including background processes.

The flowchart visualizes the system's boundaries and the distinction between background and foreground systems. The cotton fiber output from the system is the reference flow, 1000 kilograms (kg) cotton fiber cultivated conventionally. A cotton yield specifically derived for conventional cotton production in Turkey was not found. Therefore, the data was acquired from Ecoinvent as 2671kg/ha. This is generally 30% larger than the average cotton yield presented for Turkey by the USDA at 1922kg/hectare (ha) (USDA, 2023b). A sensitivity analysis on the yield was performed, further explained in section 4.3.6.

The input values to the cultivation process are based on an Ecoinvent 3.9.1 dataset. It is a dataset representing a global, in Ecoinvent named Rest-of-World (RoW), average cotton cultivation system. It is called *seed-cotton production, conventional - RoW - seed-cotton* and is based on the three major cotton providers in the world, namely the USA, India, and China. The dataset is described as an aggregation of the best available technology for modern cotton cultivation and was chosen in the absence of first-hand data.

4.2.1.1 Preperation and sowing

Cultivation starts with preparing the field, plowing and hoisting the field, and planting the cottonseeds. Generally, Turkey's cotton production is mainly mechanized, as described by Erdogan (2023), and all processes were assumed to be mechanized. This step begins directly after the harvest of the previous crop. The machinery used for this was given through the Ecoinvent dataset, together with the energy required to run them, and the machines were assumed to run on diesel. The fuel consumption of the specific machines was provided by Nemecek et al. (2019) guidelines "Methodological Guidelines for the Life Cycle Inventory of Agricultural Products." The diesel production and consumption were based on EU datasets and are presented in Appendix A.

4.2.1.2 Field operation

The field operations are all presented as a linear process in figure 4.2, with irrigation, fertilization, and pesticide spraying. This is an illustration and separation used for the LCA application. In reality, these things happen on several occasions throughout the cultivation process.

The irrigation was assumed to be done via furrow irrigation, as it is mentioned as the most commonly used type of irrigation for Turkish cotton farming (Erdogan, 2023). Furrow irrigation is an irrigation procedure where water flows in uniformly spaced furrows between the crops (Friedman, 2023). The water was assumed to originate from groundwater and rivers, as described in the Ecoinvent data. The water pump was assumed to be electric, and the electricity consumption of a generic water pump was given by Nemecek et al. (2019). The electricity generation used in the process was based on Turkey's national electricity mix, as supplied by GaBi.

The type and amount of fertilizers used in the cultivation were provided from the Ecoinvent dataset of cotton cultivation. It sums up to the approximate amount of 90 kg N, 50 kg P_2O_5, and 21 kg K_2O per ha. The emissions were calculated through emission models provided by Nemecek et al. (2019). The production processes of fertilizers were given through datasets provided by Ecoinvent and GaBi; these datasets' specifications are provided in Appendix A. The fertilization is assumed to be performed by a sprayer, also running on diesel.

Current data on pesticide use in Turkey was complex to acquire, and the pesticides are based on the description by Kooistra et al. (2006). The total amount of pesticides used was based on Ecoinvent data, an amount of around 3.6 kg/ha, and the background process used for the production was the Ecoinvent 3.8 dataset *RER: pesticide production, unspecified* due to the issues of finding pesticide-specific production processes. For the emissions from pesticide use, the assumption was made that 100% of the active ingredient in pesticides applied are emitted to agricultural soil (Nemecek et al., 2019). The total output was divided equally among the pesticides used in Turkey and available in GaBi as described by Kooistra et al. (2006). The specific pesticides were Carbosulfan, Endosulfan, Fluazifob butyl, Lambda-cyhalothrin, Linuron, Prometryne, Thiodicarb, and Trifluralin.

4.2.1.3 Harvesting and Ginning

The harvesting is assumed to be done by a combine harvester running on diesel. The ginning process is based on the Ecoinvent 3.9.1 dataset *fibre production, cotton, ginning - RoW - fibre, cotton.* It is also provided as an average of the ginning practices in the USA, China, and India.

4.2.2 Organic cotton system

The organic cotton production is presented in the flowchart (figure 4.2).

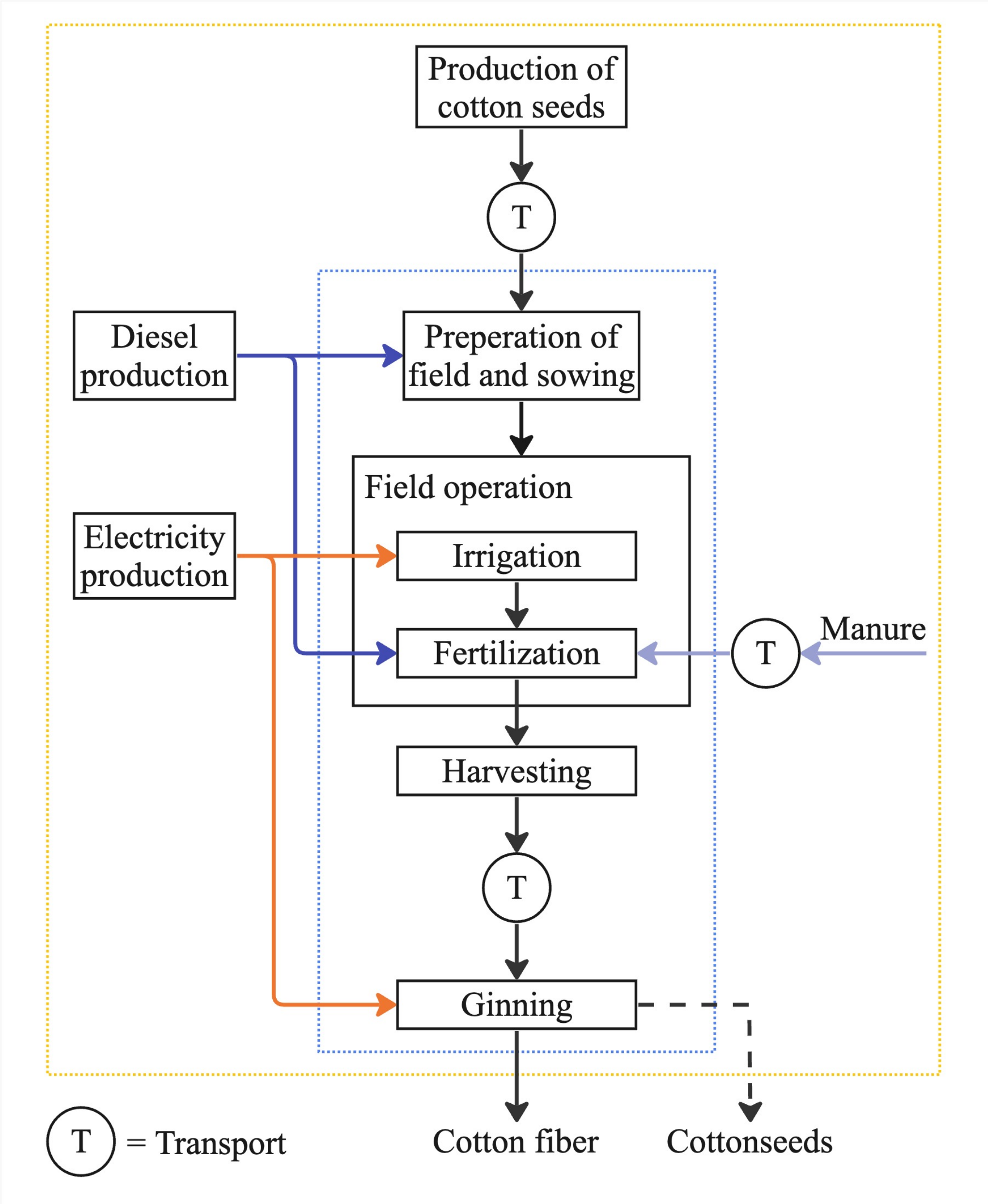


Figure 4.3: Flow chart for the organic cotton process. The blue box represents the foreground system boundaries, and the yellow box represents the total system boundary, including background processes.

The cotton yield for organic cotton was derived from a study presented by Textile Exchange covering the total amount of organic cotton produced in Turkey and the total amount of organically certified areas (Exchange, 2022). In 2020/2021, Turkey cultivated 80830 tonnes of organic cotton fiber on 43329 has of land. This gives a yield of 1866 kg/ha.

The cultivation process is based on the Ecoinvent 3.9.1 dataset *seed-cotton production, organic - RoW - seed-cotton, organic*, a dataset of organic cotton cultivation based on an organically certified farm in India. However, alterations were made to the dataset to include such things as machinery and irrigation to better align with the organic cultivation practices in Turkey.

4.2.2.1 Preperation and sowing

Organic cotton production starts with the preparation of the field right after the harvest of the previous crop. It is assumed that ridge tillage is used in the cultivation. Ridge tillage is a conservation tillage method that means the construction of raised ridges on which the crop is planted (Carter, 2005; Gilley, 2005). The crop is planted on the same ridges yearly to decrease soil disturbance. Therefore, no-tillage by machine or hand was assumed to happen. The seeds are planted through the use of agricultural machinery using diesel. Diesel production and consumption are based on EU values, similar to the conventional process.

4.2.2.2 Field operations

Similarly to the conventional process, the field operations are presented as a linear process of first irrigation and fertilization. The irrigation is assumed to be done via furrow irrigation, similar to the conventional system. The water pump used is assumed to run on electricity, and the amount of electricity is taken from Nemecek et al. (2019). The fertilization is mechanized and runs on diesel. The amount and type of fertilizers are taken from the Ecoinvent database as ca 5000kg/ha of cattle manure.

4.2.2.3 Harvest and Ginning

The harvesting is assumed to be done by a combine harvester. The ginning is modeled in the same way as for the conventional cotton (see section 4.2.1.3)

4.3 Life Cycle Impact assessment

The following section will describe the values and equations used to calculate the environmental impact. First, the ecoregions considered will be presented, followed by the three models, ReCiPe, C&B, and HF, followed by a description of the sensitivity analysis.

4.3.1 Ecoregions in Turkey

Both C&B and HF divide the impacts over terrestrial ecoregions based on the ecoregion map developed by Olson et al. (2001) (Chaudhary & Brooks, 2018; Kuipers et al., 2021). Turkey is a large nation that spans several ecoregions. For this study, a few specific regions were chosen based on Turkey's two most prominent areas for cotton production, Aegean and Southeast Anatolian regions (Erdogan, 2023; Günaydin et al., 2019; USDA, 2023b). The chosen ecoregions were based on the significant regions in these two cotton-producing areas (Earth, n.d.; Zeydanlı & Ülgen, 2009).

Table 4.2: Ecoregions considered in the study.

Ecoregions of Turkey
Aegean and Western Turkey Sclerophyllous and Mixed Forest
Anatolian and Western Turkey Sclerophyllous and Mixed Forests
Eastern Mediterranean Conifer-Sclerophyllous-Broadleaf Forest
Southern Anatolian Montane Conifer and Decisious Forests

4.3.2 ReCiPe2016

The ReCiPe2016 model's endpoint impact category, "Damage to ecosystems," was examined in the LCIA. The endpoint factor is presented in the unit species.yr. The endpoint CFs per impact category provided by Huijbregts et al. (2017) are presented in table 4.3. The hierarchic perspective was chosen in the ReCiPe2016 model.

Table 4.3: ReCiPe2016 endpoint CFs per impact category.

Mid-point impact	**CF**	**Unit**
Ecosystem quality: Terrestrial		
Climate change	2.8E-09	species.yr/kg CO_2 air
Ecotoxicity	5.4E-08	species.yr/kg 1,4-DCB to industrial soil
Water use	1.4E-08	species.yr/m^3 water consumed
Acidification	2.1E-07	species.yr/kg SO_2 to air
Photochemical ozone formation	1.3E-07	species.yr/kg NO_x to air
Land use	8.9E-09	species/m^2 annual cropland
Ecosystem quality: Freshwater		
Climate change	7.7E-14	species.yr/kg CO_2
Eutrophication	6.1E-07	species.yr/kg P to freshwater
Ecotoxicity	7.0E-10	species.yr/kg 1,4-DCB to freshwater
Water use	6.0E-13	species.yr/m^3 water consumed
Ecosystem quality: Marine		
Ecotoxicity	1.1E-10	species.yr/kg 1,4-DCB to marine water
Eutrophication	1.7E-09	species.yr/kg P to freshwater

4.3.3 C&B

To calculate the biodiversity impact using the C&B method, taxonomy-specific and aggregated CFs were collected for the four ecoregions under study (see table 4.2), from Chaudhary et al. (2018). Regarding the three different intensity levels provided by C&B (see table 2.2 in section 2.5), two levels were chosen in the study. For the conventional process, the level *intese use* was chosen due to the use of pesticides and chemical fertilizers along with the irrigation and mechanization. For the organic system, the level *light use* was selected due to the assumptions of large-scale farming, including mechanization, monoculture cropping, no crop rotation, etc. The implications of these choices will be examined through a sensitivity analysis.

The aggregated, average, global characterization factors for C&B for the four different ecoregions and three different intensity levels are provided in table 4.4 for both the occupation and transformation.

Table 4.4: Occupational CFs used in the C&B method for the four different ecoregions and the three intensity levels measured in PDF/m^2.

Ecoregion	Minimal	Light	Intensive
Occupation[PDF/m^2]			
Aegean and Western Turkey	8.33E-14	9.11E-14	9.23E-14
Anatolian	6.59E-14	7.33E-14	7.43E-14
Eastern Mediterranean	1.48E-13	1.63E-13	1.66E-13
Southern Anatolian	1.91E-13	2.12E-13	2.15E-13
Transformation[PDF*yr/m^2]			
Aegean & Western Turkey	1.68E-11	1.84E-11	1.86E-11
Anatolian	1.31E-11	1.46E-11	1.48E-11
Eastern Mediterranean	3.03E-11	3.33E-11	3.37E-11
Southern Anatolian	3.85E-11	4.26E-11	4.32E-11

These CFs were then multiplied by the amount of land used to cultivate 1000kg cotton conventionally and organically through equation 4.1.

$$I_{C\&B,i,j} = (CF_{occ,i,j} * A_{fu}) + \frac{CF_{trans,i,j} * A_{fu}}{years_{trans}} \tag{4.1}$$

In this equation, $CF_{occ,i,j}$ and $CF_{trans,i,j}$ refers to the occupation and transformation CFs as provided in table 4.4, A_{fu} the area needed for the cultivation of the functional unit of the system and the $years_{trans}$ the number of years that the cropland is in use. As mentioned in section 4.1.2.5, the LCA assumes no transformation impact. However, these values and calculations will be used for the sensitivity analysis and are therefore provided.

4.3.4 Habitat Fragmentation

To calculate the biodiversity impact with the HF model, CFs were collected from Kupiers et al. (2021) for the four ecoregions. The global average values were chosen to keep it consistent with the other models, and since this is an attributional LCA, the average values are preferred. HF does not distinguish between intensity levels; therefore, the same CFs are applied for both processes. The CFs used in the model are presented in table 4.5.

Table 4.5: Transformation and occupation CFs used in HF for the four ecoregions.

Ecoregion	Occupation [PDF/m^2]	Transformation [PDF*yr/m^2]
Aegean & Western Turkey	3,49E-15	7,12E-13
Anatolian	3,87E-16	8,07E-14
Eastern Mediterranean	6,03E-15	1,24E-12
Southern Anatolian	5,82E-15	1,19E-12

These CFs were then multiplied with the amount of land used in the cultivation step similarly to for C&B presented in equation 4.2.

$$I_{HF,i,j} = (CF_{occ,i,j} * A_{fu}) + \frac{CF_{trans,i,j} * A_{fu}}{years_{trans}} \tag{4.2}$$

4.3.5 Comparison of the three models

It was interesting to compare the three models' calculated land use impacts to examine how they differ. Unfortunately, comparing them straight meant wrongful and unfair comparisons due to differences in endpoint units and calculation assumptions. They were, therefore, recalculated into the final unit species.yr in the comparison. Since the ReCiPe2016 model already provides the results in this factor, the ReCiPe2016 values were consistent in the comparison.

For the C&B model, the taxonomy-specific CFs provided by Chaudhary et al. (2018) were chosen to acquire the unit species.yr. Furthermore, the values were divided by the VS values for every taxonomic group. Finally, the calculated values per taxonomic group were summed to provide an aggregated value for comparison with ReCiPe2016 and HF for the total species loss.

For the HF model, the regional CFs were considered to enable comparison. These were provided by Kuipers et al. (2021). These values were multiplied by the total available species per taxonomic group in the ecoregion to acquire values in species.yr. Finally, the calculated values per taxonomic group were summed to provide an aggregated value for comparison with ReCiPe2016 and C&B for the total species loss.

4.3.6 Sensitivity analysis

Three different sensitivity analyses are made to analyze the robustness of the results. The motivation behind these sensitivity analyses and how they will be performed are presented below. The results of the analyses will be presented in chapter 5

4.3.6.1 Including Land Transformation

In the study, the impact of land transformation is excluded due to the limited data on the longevity of cotton cultivation fields. However, land transformation is an important aspect, so a sensitivity analysis was performed that included land transformation impacts in the cotton cultivation processes.

The sensitivity analysis will be performed by adding a factor of land transformation allocated over one year, ten years, and twenty years. According to the USDA (2023b), the area where cotton is cultivated has fluctuated but generally increased slightly since 2013/2014. This likely means that many regions have cultivated cotton for over ten years, so ten years was chosen. 20 years is the suggestion from the "UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA" by Koellner et al. (2013) that suggest 20 years as a fitting allocation period based on standards and regulations for carbon dioxide emissions from land use.

4.3.6.2 Change in cotton yield

The second sensitivity analysis that was performed was yield. As mentioned in section 2.7.1, the yield gap between conventional and organic cotton is a discussed trade-off in the comparison. Therefore, the yield and, subsequently, the area needed for cultivation is a factor of interest. In the model used, the yield difference was 35.5%. This sensitivity analysis will be performed by lowering the conventional yield so it is nearly 15% higher than the organic, to 2146 kg/ha. This value was chosen for two reasons. Firstly, it is nearly halfway between the conventional and organic base-level yields, making for a good interim value. Secondly, as mentioned in section 2.7.1, the yield difference between organic and conventional agricultural practices has been shown to vary between 5-34% and 15% is then a good estimated mid-value.

4.3.6.3 Intensity Level

The third sensitivity analysis will be made by changing the intensity level chosen. This is only relevant for C&B because HF and ReCiPe2016 do not distinguish between different intensity levels. As described in section 4.3.3, the intensity level for the process of questions is light and intense for organic and conventional farming, respectively. The organic impact will be calculated through the minimal intensity, and the three different outcomes will be compared: the minimal and the two base case results.

5
Results

This chapter will present the results of the LCIA for the three different models used to compare conventional and organic cotton. The results following the ReCiPe2016 model will first be presented, followed by the C&B, the HF, and the comparison of the three models. Finally, the results of the sensitivity analysis will be presented.

5.1 ReCiPe2016

The ReCiPe2016 results are presented below, starting with the total cumulative impact of the two processes, followed by a deep dive into the single processes. Figure 5.1 shows the total impact of the conventional and the organic cotton production processes divided per impact category and presented in the ReCiPe2016 Damage to ecosystem endpoint value species.yr/1000kg cotton fiber. The results show that the total impact of the conventional process is higher.

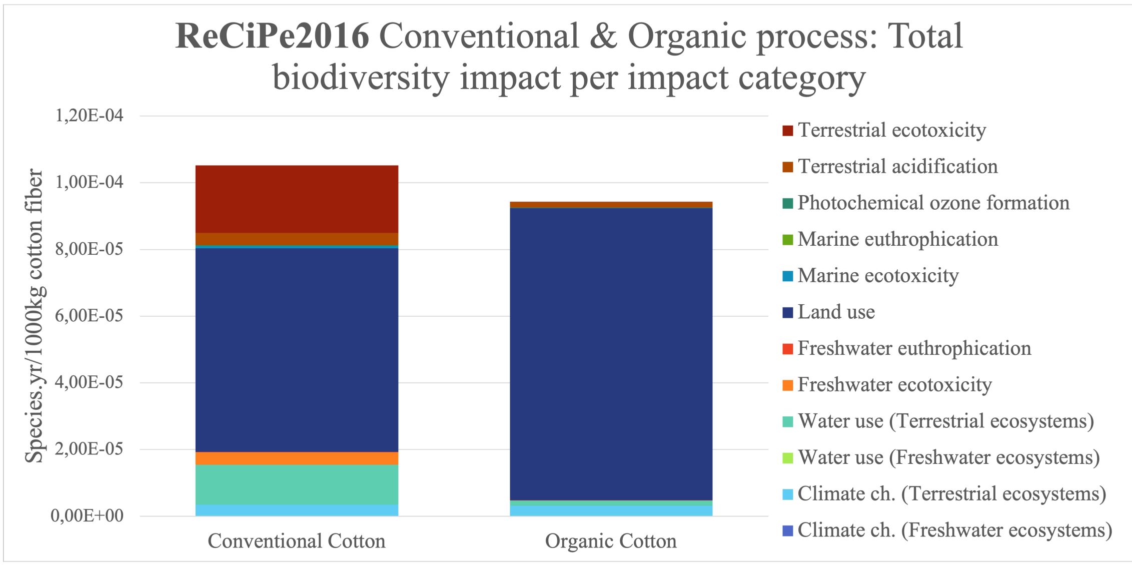


Figure 5.1: The total impact on ecosystem quality per impact category for the conventional and organic process.

Analyzing the impacts across the included categories and comparing them between the conventional and organic shows the different contributions to the total impact, offering insights into the reasons behind the more considerable total impact from the conventional process. The land use category emerges as the primary contributor to the total impact of both processes. Notably, in the organic process, land use yields a more prominent impact than in the conventional process, followed by minor impacts from terrestrial acidification, climate change impact on terrestrial ecosystems, and freshwater consumption on terrestrial ecosystems. In the conventional process, land use is the most impactful, succeeded by terrestrial ecotoxicity and freshwater consumption in terrestrial ecosystems. Subsequently, terrestrial acidification, freshwater ecotoxicity, and the impact of climate change on terrestrial ecosystems follow suit. These impact categories collectively contribute to the higher overall impact observed in the conventional process.

Table 5.1 provides the numerical values expressed in species.yr/1000kg cotton fiber of the different impacts for the conventional and organic process, respectively. Looking at the total impact provided in the table, the total numerical difference in amount shows the organic cotton process impact to be 11% lower than the conventional one. By examining the percentual difference between the conventional and the organic, it is clear that for all impacts except land use and marine eutrophication, the impacts are larger for the conventional, sometimes nearly 200% larger. The reason for the higher values, especially for ecotoxicity and acidification, is the increased amount of fertilizer and pesticide use in the conventional process. This can also be seen in the impact values for the background and foreground processes in Appendix B. The impacts from the water use are 153% lower for the organic process. This is mainly due to the difference in the amount of irrigation water provided by the different data sources used in the conventional and organic inventory. The climate change impacts relate primarily to transportation and machinery emissions, diesel production, and energy and electricity production. Since transport, machinery, electricity, and energy are used in similar amounts in both processes, the differences are not as significant as for other impact categories.

Table 5.1: The total impact of the conventional and organic processes presented per impact category, including the difference in % from conventional to organic.

Impact category	Conventional	Organic	Difference
Terrestrial ecotoxicity	2,02E-05	7,40E-08	-198
Terrestrial acidification	3,70E-06	1,59E-06	-198
Photochemical ozone formation	3,10E-07	2,28E-07	-80
Marine eutrophication	2,81E-09	3,59E-09	+24
Marine ecotoxicity	5,98E-07	2,31E-09	-199
Land use	6,11E-05	8,76E-05	+36
Freshwater eutrophication	1,22E-07	5,32E-08	-79
Freshwater ecotoxicity	3,71E-06	1,42E-08	-198
Water use (Terrestrial Ecosystems)	1,20E-05	1,58E-06	-153
Water use (Freshwater Ecosystems)	2,93E-09	3,93E-10	-153
Climate ch. (Terrestrial Ecosystems)	3,52E-06	3,16E-06	-10
Climate ch. (Freshwater Ecosystems)	9,59E-11	8,64E-11	-10
TOTAL	1,05E-04	9,43E-05	-11

Figure 5.2 illustrates the impact of various process steps as outlined in the flow

chart depicted in Figure 4.2. Upon initial observation, it becomes apparent that the crucial process steps encompass preparation and sowing, irrigation, and fertilization.

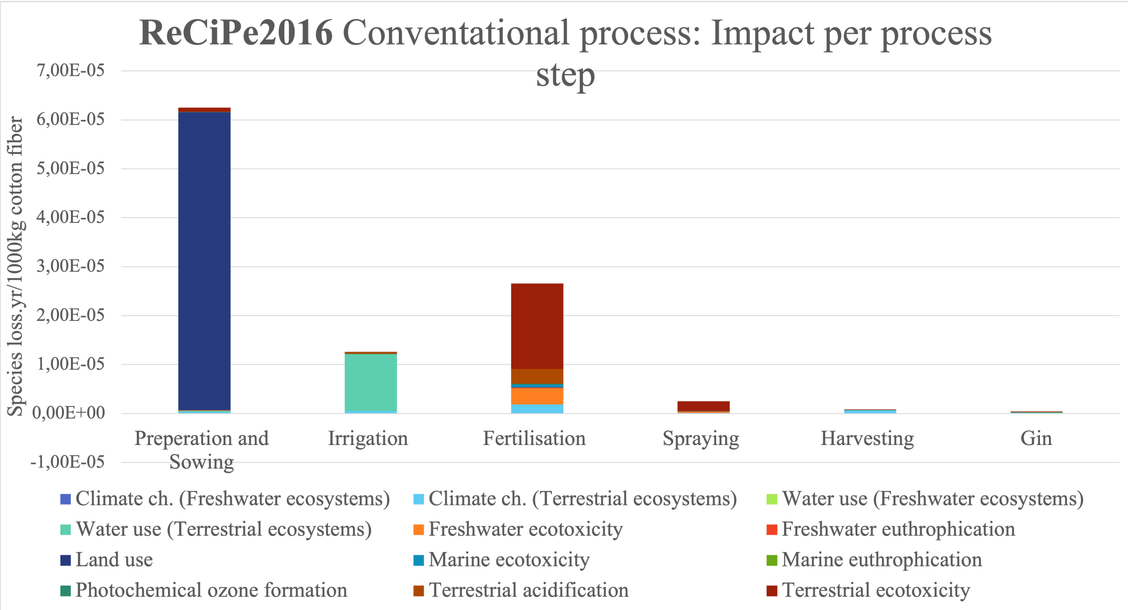


Figure 5.2: Impact per process step presented per impact category for conventional process.

Beginning with the preparation and sowing stage, land use emerges as the most significant factor, primarily because all land use for cultivation was allocated to this step. In the irrigation phase, the impact is predominantly driven by freshwater consumption in terrestrial ecosystems. The notably minimal contribution from freshwater consumption on freshwater ecosystems can be explained by a much smaller mid- to endpoint CF used in the water use impact on freshwater ecosystems as can be seen in table 4.3. The fertilization stage exhibits a more diverse impact, with terrestrial ecotoxicity leading, followed by freshwater ecotoxicity, terrestrial acidification, and climate change. Spraying exhibits a comparatively minor impact compared to the previously mentioned stages, primarily contributing through terrestrial and freshwater ecotoxicity. As for the harvesting and ginning processes, climate change impacts on terrestrial ecosystems exhibit the largest contribution.

Auxiliary production includes the production of energy, electricity, pesticides, fertilizers, and seeds. Figure 5.3 shows the portion of the foreground system, auxiliary production, and transport. The contribution from auxiliary production mainly arises from terrestrial ecotoxicity, where the production of fertilizers used in the system contributes to a significant impact. The impacts divided upon foreground and background systems can be found in Appendix B.

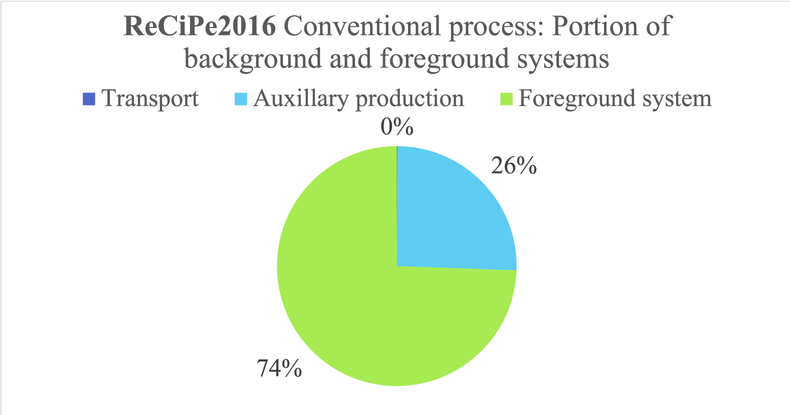


Figure 5.3: Portion of auxiliary processes, foreground processes, and transport for the conventional process.

Moving forward, figure 5.4 presents the organic production process and its impacts across its specific process steps. The impact of land use during preparation and sowing is notably the most substantial. Similarly to the outcomes observed in conventional production, the entire extent of cultivation land use is allocated to the preparation and sowing stage, explaining its substantial contribution. Irrigation emerges next, with the most significant impact stemming from freshwater consumption. Fertilization mainly contributes to climate change effects on terrestrial ecosystems and terrestrial eutrophication. Regarding harvesting and ginning, their contributions mirror those in the conventional process, with primary impacts linked to climate change and terrestrial acidification; however, they are notably smaller in comparison to the significant impact of land use.

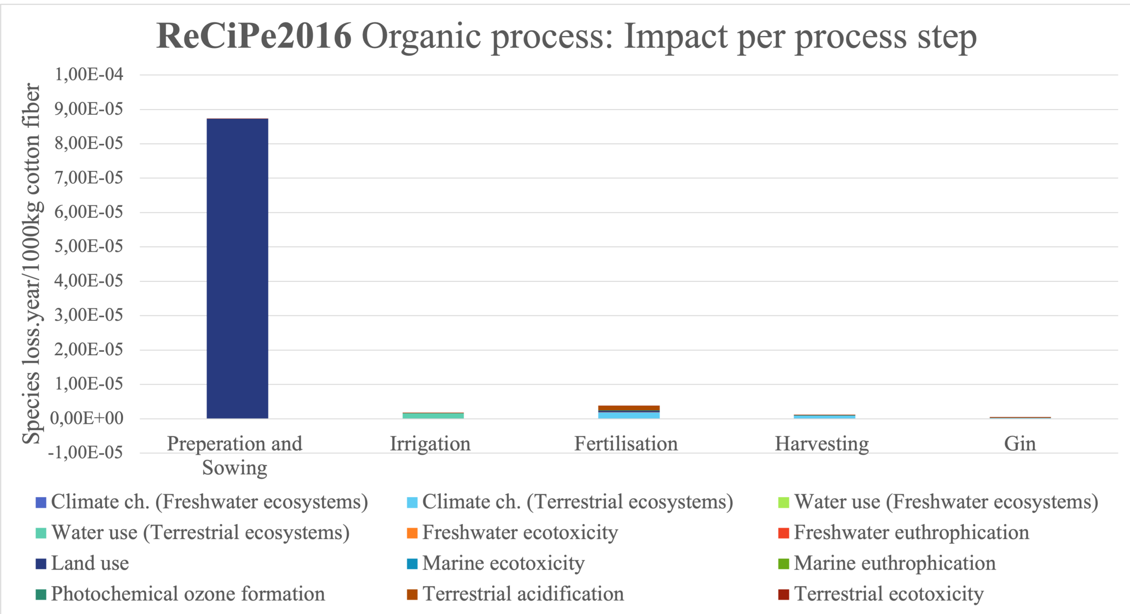


Figure 5.4: Impact per process step presented per impact category for the organic process.

Looking at the proportion of the auxiliary process, transport, and foreground systems of the total impact, shown in figure 5.5, the largest part of the impact comes from the foreground system with the auxiliary process and transport sharing ca 3% of the total impact. This was expected as, compared to the conventional process, the organic doesn't require chemical fertilizers and pesticide production. The fertilizer used in the organic process enters the system without impact, as explained in section 4.1.2.4.

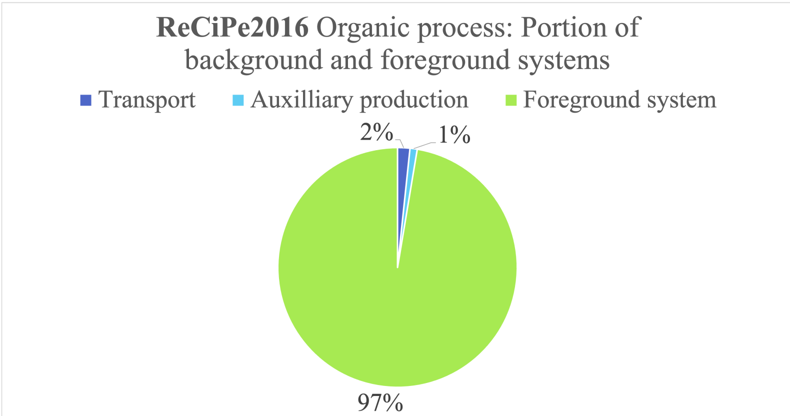


Figure 5.5: Portion of auxiliary processes, foreground processes, and transport for the organic process.

5.2 C&B

The following results present the land use impact assessment based on C&B. Figure 5.6 presents the total land use impact of the conventional and organic cotton production processes, the values, and the difference between the two systems for all four ecoregions. Based on this result, the impact from the organic is far larger for all four ecoregions. The difference between the two processes, at a value of around 34% for all four ecoregions, is based on the difference in yield, at 35.5%, and the difference in CFs following the choice of intensity factors. The difference in CFs between light and intense land use constitutes a value of around 1.22-1.38%. (see table 4.4 in section 4.3.3). The difference in intensity levels is based on habitat affinity, and as can be seen in table 2.1 in section 2.5, the average taxon affinity values for the three different intensity levels don't differ significantly potentially explaining the minor difference between intensity factors and the fact that the intensity levels did not overrule the yield.

There is also a variation between the ecoregions where the Southern Anatolian region represents the largest impact, followed by the Eastern Mediterranean and then the Aegean and Western Turkey, and finally, the Anatolian presents the lowest impact. This is based on several factors, such as different VS amongst the species in the area, different amounts of species in the area, different amounts of natural land left in the ecoregion, etc.

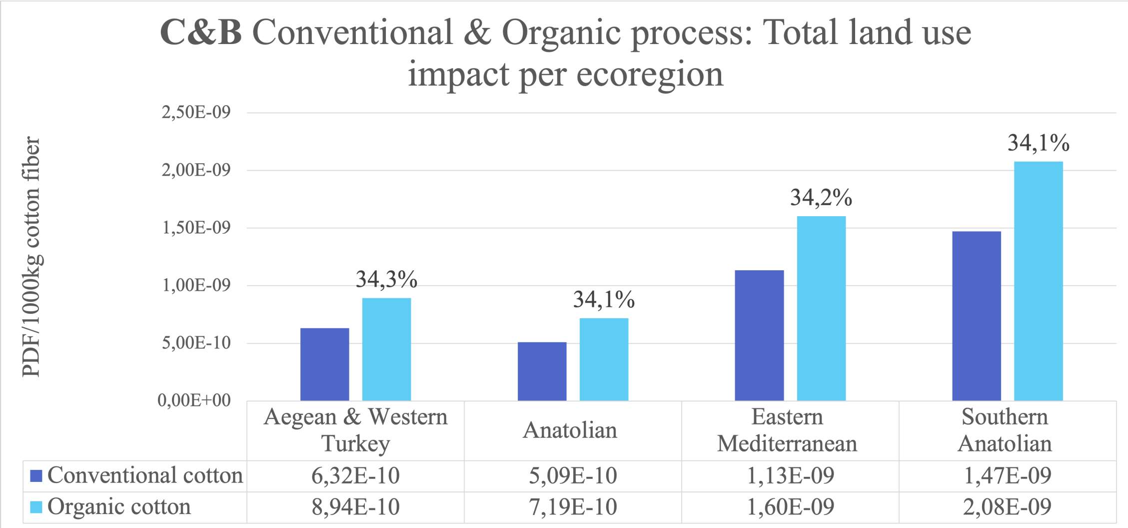


Figure 5.6: Total land use impact of the conventional and organic cultivation processes for the four chosen ecoregions, C&B model.

The impact of the different taxonomic groups for the four different ecoregions is shown in 5.7 for the conventional and in figure 5.8 for the organic process. Both are presented in PDF/1000kg cotton fiber. Both figures show that the impact upon the amphibians shows the largest relative impact for both processes and that the difference between ecoregions follows the same pattern as for the total amount. Birds consistently have the smallest impact on the ecoregions, followed by mammals, reptiles, and plants.

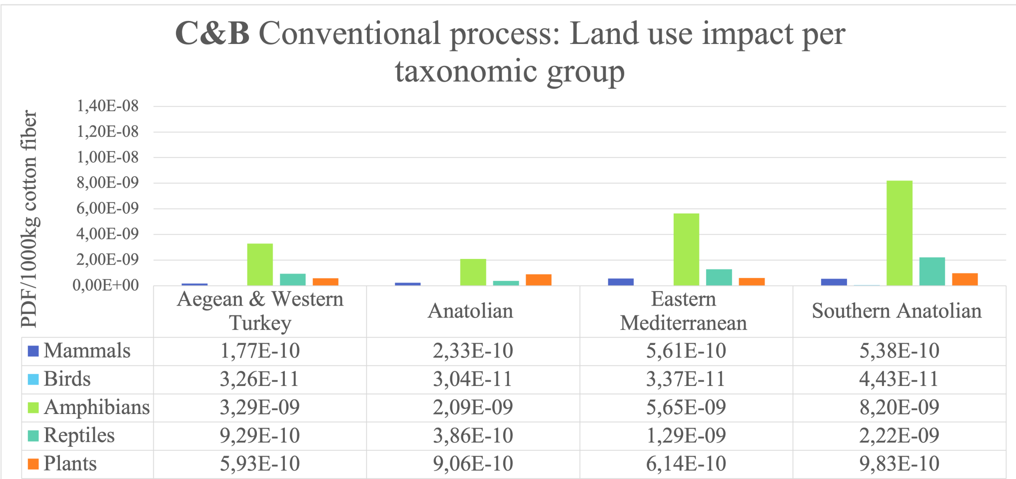
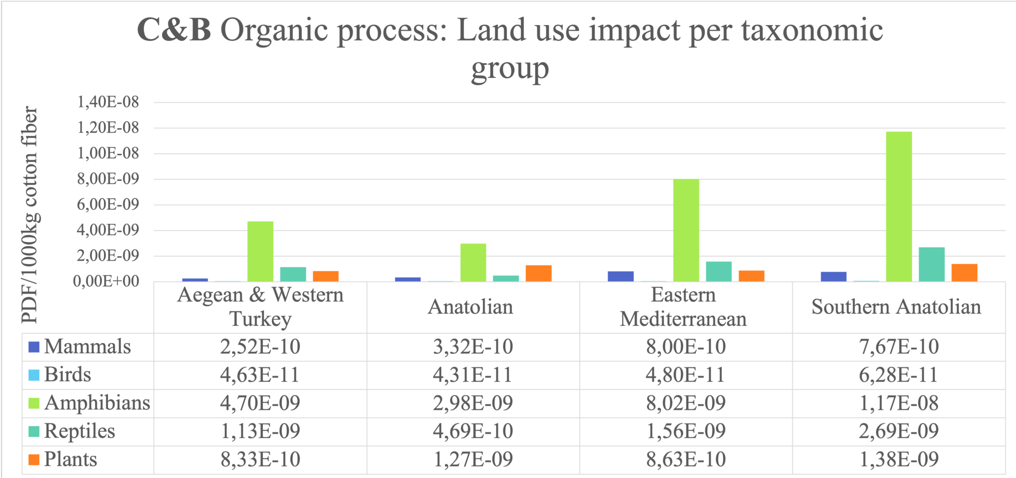


Figure 5.7: Taxa specific land use impact of the conventional process for the four different ecoregions, C&B model.

The organic process shows a larger impact consistently over all taxonomic groups; however, it follows the same pattern as for the conventional one. Again, the largest difference in this distinction is the yield gap between the conventional and organic since the intensity level differences in CF are very small.

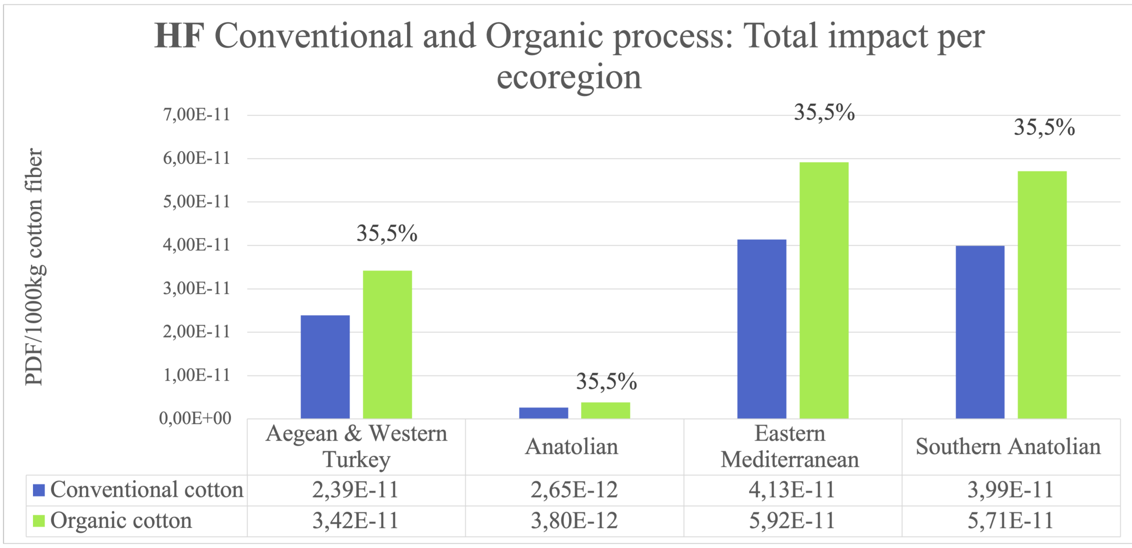


	Aegean & Western Turkey	Anatolian	Eastern Mediterranean	Southern Anatolian
Mammals	2,52E-10	3,32E-10	8,00E-10	7,67E-10
Birds	4,63E-11	4,31E-11	4,80E-11	6,28E-11
Amphibians	4,70E-09	2,98E-09	8,02E-09	1,17E-08
Reptiles	1,13E-09	4,69E-10	1,56E-09	2,69E-09
Plants	8,33E-10	1,27E-09	8,63E-10	1,38E-09

Figure 5.8: Taxa specific land use impact of the organic process for the four different ecoregions, C&B model.

5.3 HF

This section will present the results of the LCIA using the HF method. Figure 5.9 shows the total land use impact of the four different ecoregions for the conventional and organic processes, together with the values and the difference between the two systems. Since HF doesn't make a difference between intensity levels of farming, the difference between the two results is the same as the difference between the amount of land needed, consistently 35%.

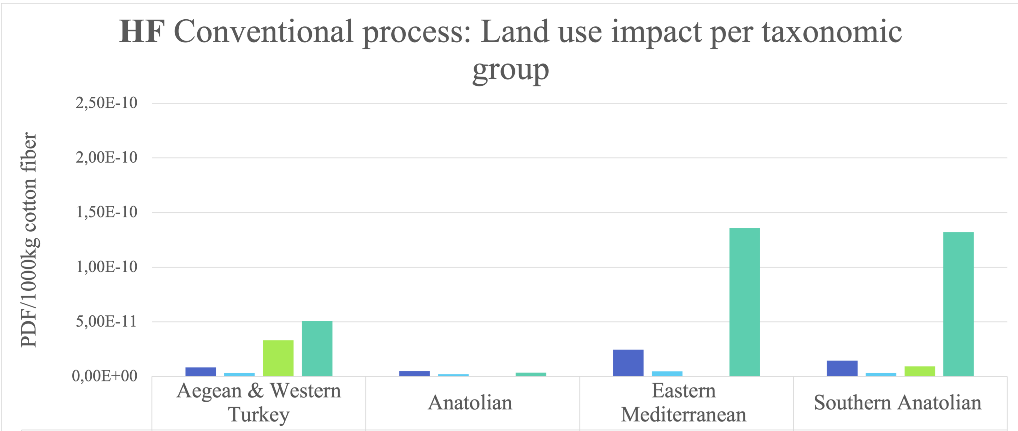


	Aegean & Western Turkey	Anatolian	Eastern Mediterranean	Southern Anatolian
Conventional cotton	2,39E-11	2,65E-12	4,13E-11	3,99E-11
Organic cotton	3,42E-11	3,80E-12	5,92E-11	5,71E-11

Figure 5.9: Total land use impact of the conventional and organic cultivation processes for the four chosen ecoregions, HF model

The results indicate that the Anatolian region has a lower impact than the other three regions, nearly 160% lower than the second lowest Aegean and Western Turkey. This depends on the GEP value for the Anatolian region. The lower value of the Anatolian region can be seen in the global CFs presented in 4.5. However, when considering regional CFs, the gap is less significant, suggesting an influence of the GEP value that translates the regional impacts to global impacts. After the Anatolian regions, the Aegean and Western Turkey region follows in size, followed by the Southern Anatolian region, which shows nearly the same impact as the largest one: Eastern Meditteranean.

Figure 5.10 visualizes the land use impact divided over the four taxonomic groups for the conventional system. Reptiles stand for the largest impact for the Aegean and Western Turkey, Eastern Mediterranean, and Southern Anatolian regions. Kuipers et al. (2021) mentions in the model description that there is a risk for overestimations in the CFs for reptiles and amphibians due to the low amount of available data on fragmentation effects.



	Aegean & Western Turkey	Anatolian	Eastern Mediterranean	Southern Anatolian
Mammals	8,33E-12	4,89E-12	2,45E-11	1,46E-11
Birds	3,26E-12	2,12E-12	4,86E-12	3,40E-12
Amphibians	3,31E-11	0,00E+00	0,00E+00	9,28E-12
Reptiles	5,09E-11	3,61E-12	1,36E-10	1,32E-10

Figure 5.10: Taxa specific land use impact of the conventional process for the four different ecoregions, HF model.

Amphibians don't have any impact in the Anatolian and Eastern Mediterranean regions. This is because the CFs provided for the amphibians in these regions are zero. A reason for this is not given by Kuipers et al. (2021). Birds show a consistently small impact throughout the four ecoregions, similar to C&B. The impact on mammals differs between the regions but is continuously small when compared to other taxonomic groups considered. The result for the organic process in figure 5.11 follows the same pattern as for the conventional but with an overall larger impact following the difference in area needed for the cultivation.

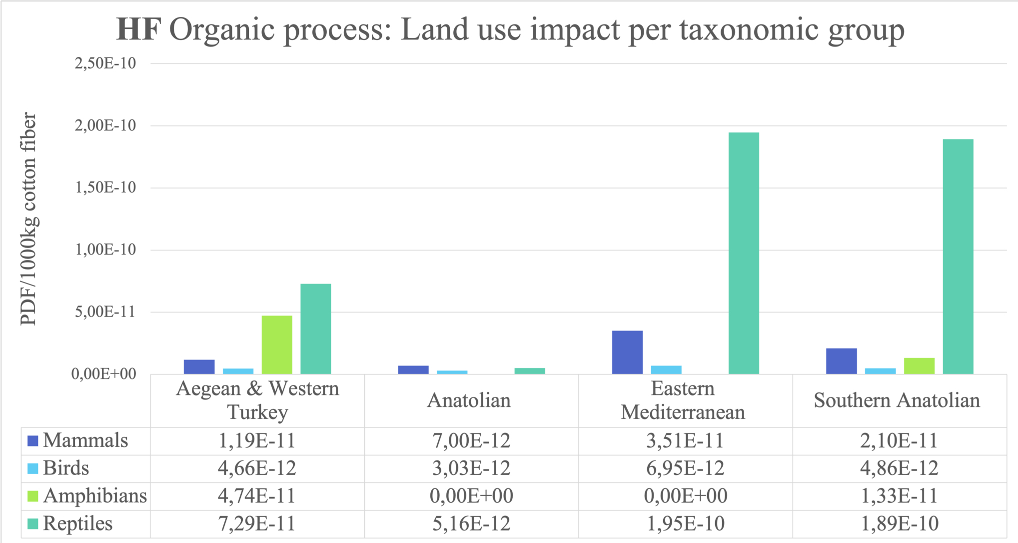


Figure 5.11: Taxa specific land use impact of the organic process for the four different ecoregions, HF model.

5.4 Comparison of the three models

The comparison of the three models required a bit of recalculation (the procedure is presented in section 4.3.5). For clarification, only the land use for cultivation will be considered from the ReCiPe2016 model to be consistent with the others. This accounts for 99,4% of the total land use impact. Figures 5.12 and 5.13 present the results of the comparison for the conventional and organic processes, respectively. The percentages indicate the difference as compared to the ReCiPe2016 model. It is evident through that table and the following figures that the values for HF are consistently lower throughout all the ecoregions.

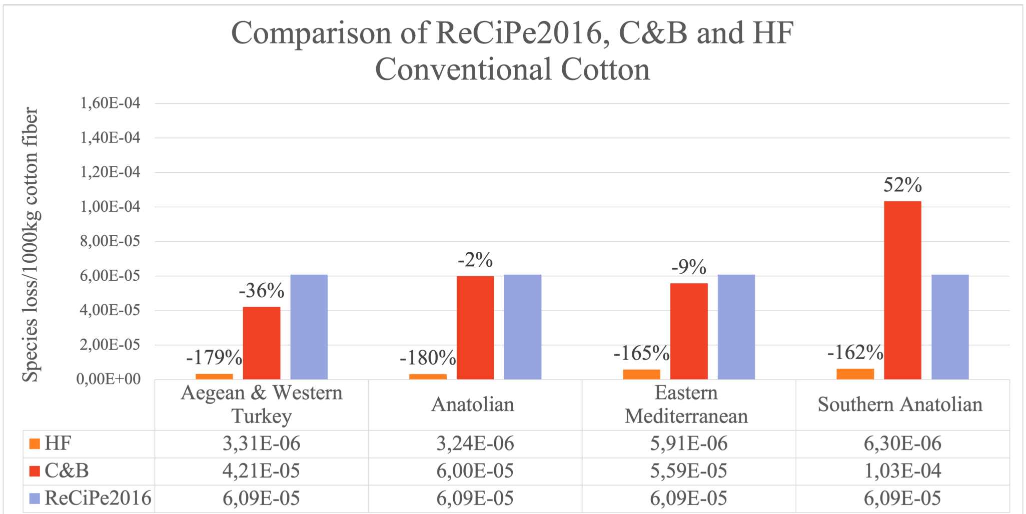


Figure 5.12: Comparison of the cultivation land use impacts between the models ReCiPe2016, HF, and C&B, conventional process.

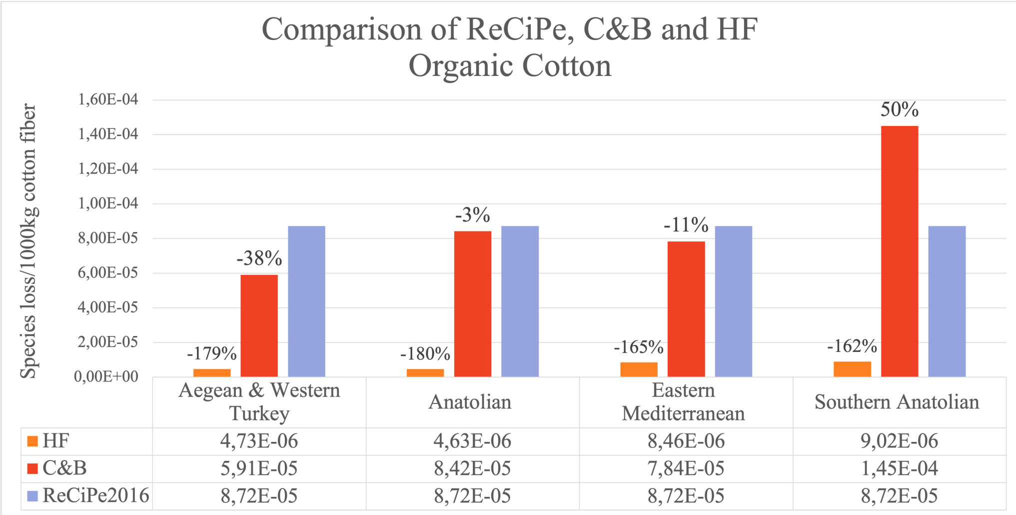


Figure 5.13: Comparison of the cultivation land use impacts between the models ReCiPe2016, HF, and C&B, organic process.

The consistently lower values from the HF model can be because HF doesn't consider plants in the model as C&B does. Tables 5.2 and 5.3 provide the taxonomy-specific regional impact values for the conventional and organic production process. It can be observed that the plants in the C&B model constitute a large impact as compared to the other taxonomic groups. Therefore, the exclusion of this will subsequently lower the total aggregated impact. Furthermore, the lower HF values can be due to certain modeling aspects. For example, the HF model considered natural fragmentation effects in natural landscapes, leading to a potentially lower natural state value than C&B.

Table 5.2: The taxonomy specific regional species loss values of the C&B and HF model for the conventional cotton process.

	Mammals	Birds	Amphibians	Reptiles	Plants
C&B					
Aegean	1,49E-06	4,47E-06	3,35E-07	6,28E-07	3,52E-05
Anatolian	1,47E-06	6,01E-06	3,15E-07	6,06E-07	5,16E-05
Eastern Meditteranean	1,80E-06	6,14E-06	1,58E-07	1,11E-06	4,66E-05
Southern Anatolian	2,19E-06	6,35E-06	3,45E-07	1,20E-06	9,33E-05
HF					
Aegean	1,45E-06	5,51E-07	3,55E-07	9,49E-07	NA
Anatolian	1,73E-06	1,04E-06	0,00E+00	4,71E-07	NA
Eastern Meditteranean	2,06E-06	1,22E-06	0,00E+00	2,63E-06	NA
Southern Anatolian	2,18E-06	1,24E-06	8,66E-08	2,80E-06	NA

Table 5.3: The taxonomy specific regional species loss values of the C&B and HF model for the organic cotton process.

	Mammals	Birds	Amphibians	Reptiles	Plants
C&B					
Aegean	2,12E-06	6,34E-06	4,79E-07	7,63E-07	4,94E-05
Anatolian	2,09E-06	8,52E-06	4,50E-07	7,36E-07	7,24E-05
Eastern Medditeranean	2,57E-06	8,73E-06	2,24E-07	1,35E-06	6,55E-05
Southern Anatolian	3,13E-06	9,00E-06	4,93E-07	1,45E-06	1,31E-04
HF					
Aegean	2,08E-06	7,89E-07	5,09E-07	1,36E-06	NA
Anatolian	2,47E-06	1,49E-06	0,00E+00	6,74E-07	NA
Eastern Medditeranean	2,95E-06	1,75E-06	0,00E+00	3,76E-06	NA
Southern Anatolian	3,12E-06	1,77E-06	1,24E-07	4,01E-06	NA

5.5 Sensitivity analysis

In the scope of this study, three sensitivity analyses were made. The results of this analysis will be presented in the following section, starting with the inclusion of land transformation, followed by a change in cotton yield, and finally, intensity level.

5.5.1 Including Land Transformation

The first sensitivity analysis examined the results of adding effects of land use transformation. In the final results, land use transformation was not added.

Starting with the ReCiPe2016 model, the figure 5.14 presents the total impact with the different allocation of land transformation. With no land transformation, there is an 11% difference between conventional and organic cotton. Following the first year allocation of land transformation, the organic cotton rose higher than the conventional by 23%; after ten years, the conventional is 1% larger, and after twenty years, 5%. Between the no transformation and first year, the impact increased by 104% for the conventional and 127% for the organic.

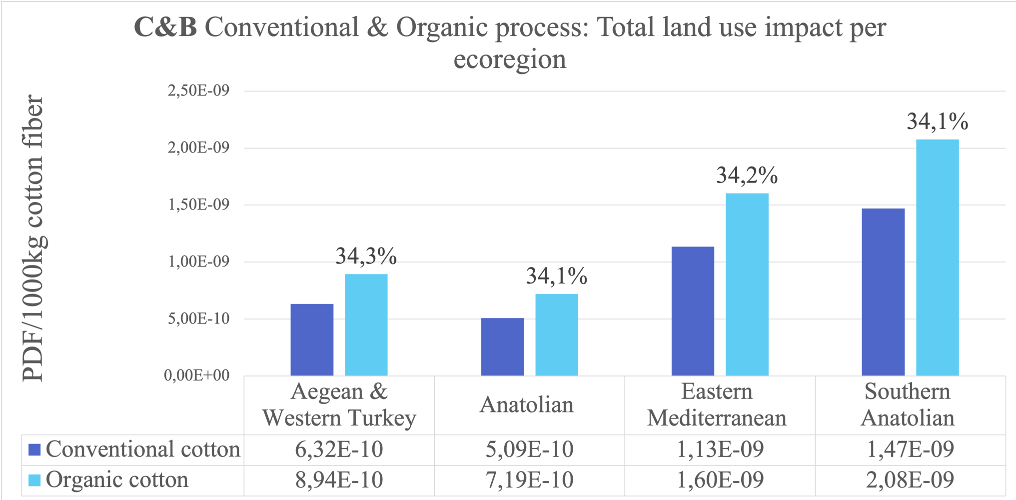


Figure 5.14: Results from including land transformation for one, ten, and 20 years using ReCiPe2016.

Moving to applying land transformation in C&B, the results will be presented only for the Southern Anatolian regions. The reason for this is that the pattern is the same for all the ecoregions, and it was therefore decided to delimit the results to only one ecoregion for clarity. Appendix B presents the results for all the different ecoregions.

Looking at the southern Anatolian region in figure 5.15, the difference between the organic and conventional are consistently around 34% for all the different land transformation allocations reflecting the 35% land amount difference as well as the minor differences in the CFs provided through the different intensity levels analyzed.

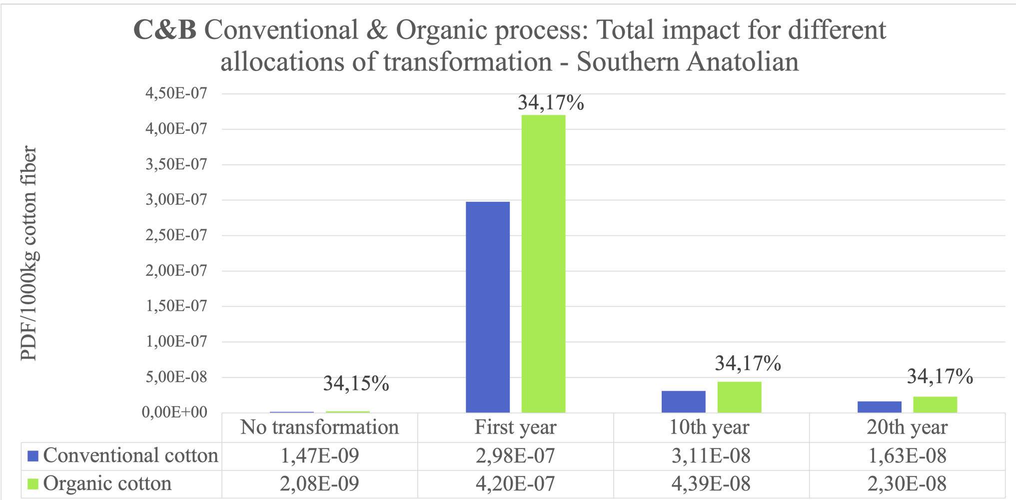


Figure 5.15: Results from including land transformation for one, ten, and 20 years using C&B for the Southern Anatolian ecoregion.

The pattern between the different allocations is similar to ReCiPe2016, with a large difference in the first year allocation followed by a large decline in the tenth and then twentieth year. From the no allocation to the first year, the impact increases by 198%. Looking at table 4.4 presenting the occupation and transformation CFs in C&B, it is clear that the transformation CFs are almost 200% larger throughout the four ecoregions and three intensity levels, meaning that a large increase in land use impact following the inclusion of transformation impacts is expected.

Moving to the addition of the land transformation in the HF model, the results will, similar to the C&B, only be presented for the Southern Anatolian region to simplify the discussion. Appendix B presents the results for all the different ecoregions. Looking at the figure 5.16, the difference between the organic and conventional is consistent throughout the transformation allocation scenarios. 35.5% reflecting the difference in area needed. The difference between the no transformation and added transformation is 198%.

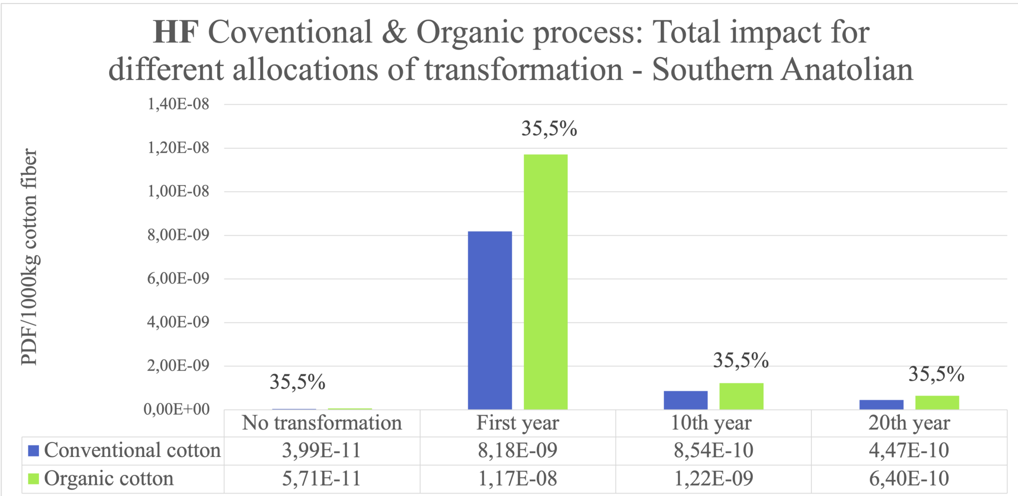


Figure 5.16: Results from including land transformation for one, ten, and 20 years using HF for the Southern Anatolian ecoregion.

5.5.2 Change in cotton yield

The second sensitivity analysis was made to analyze the effect of a changed cotton yield in the conventional process. Looking first at the ReCiPe2016 model, figure 5.17 presents the total impact of the process for the three different cotton yields, the two baselines, and the 15% lower conventional yield. The conventional with a 15% lower yield presents the highest overall impact. This makes sense because, apart from all the other impacts it shares with the baseline conventional, it also requires more land, meaning that the land use impact increases and the total impact is higher than the conventional and, therefore, also the organic.

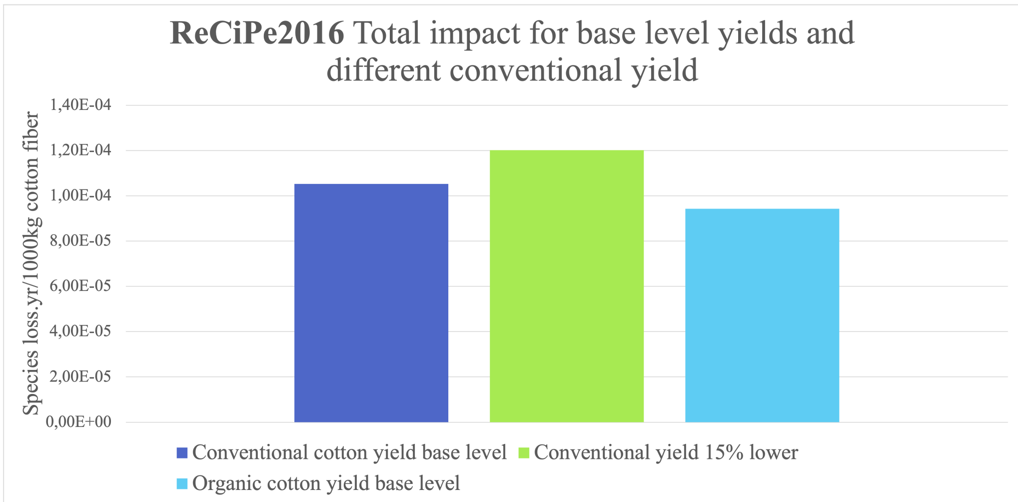


Figure 5.17: Total impact from ReCiPe2016 from the base level conventional (dark blue) and organic (light blue) process together with a 15% lower conventional yield (green).

Looking at the impact of a changed cotton yield in C%B and HF, the results are presented in figure 5.18 and 5.19 respectively. The difference between the yield scenarios also makes sense in these models. The decrease of cotton yield means that more land will be needed for the same amount of cotton meaning that the land use impact will increase. This increase is nearly linear to the increase in land required.

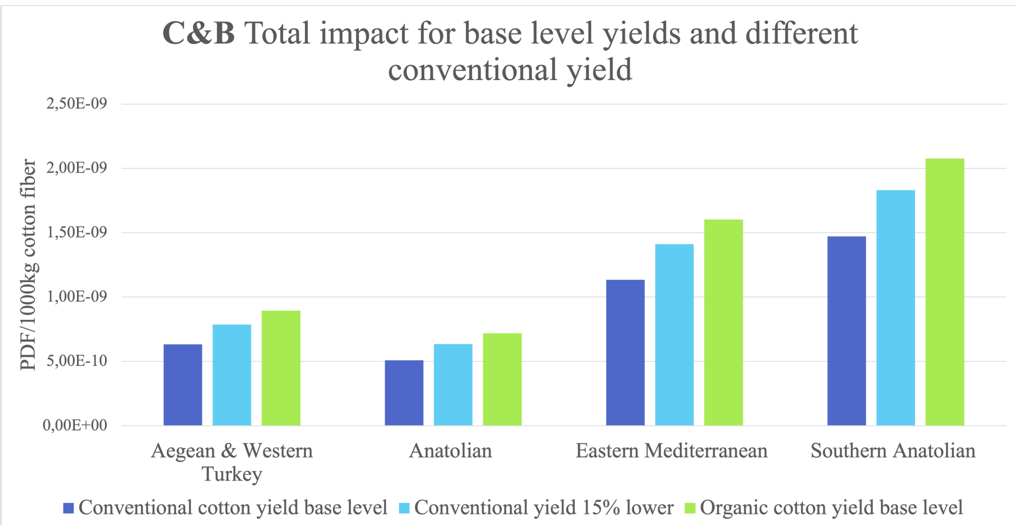


Figure 5.18: Total impact from C&B from the base level conventional (dark blue) and organic (light blue) process together with a 15% lower conventional yield (green).

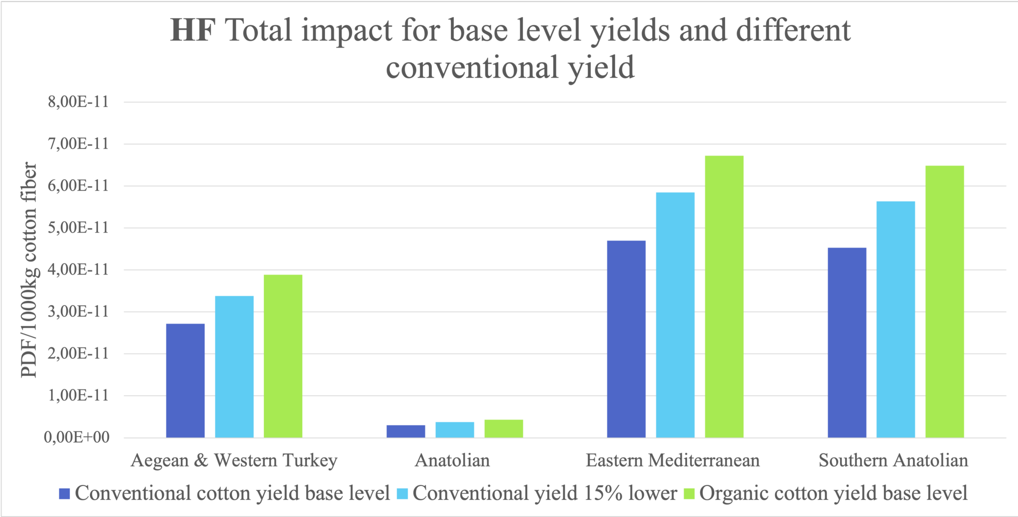


Figure 5.19: Total impact from HF from the base level conventional (dark blue) and organic (light blue) process together with a 15% lower conventional yield (green).

5.5.3 Intensity Level

In the final sensitivity analysis, the intensity levels are changed. This only affects C&B because, as mentioned in the report, HF and ReCiPe2016 do not distinguish between intensity levels.

The three different intensity levels were described in section 4.3.3, and for this study, light was chosen for the organic, and intensive was chosen for the conventional. In this sensitivity analysis, the organic cotton farming was also calculated with the minimal land intensity level selected. Figure 5.20 presents the difference.

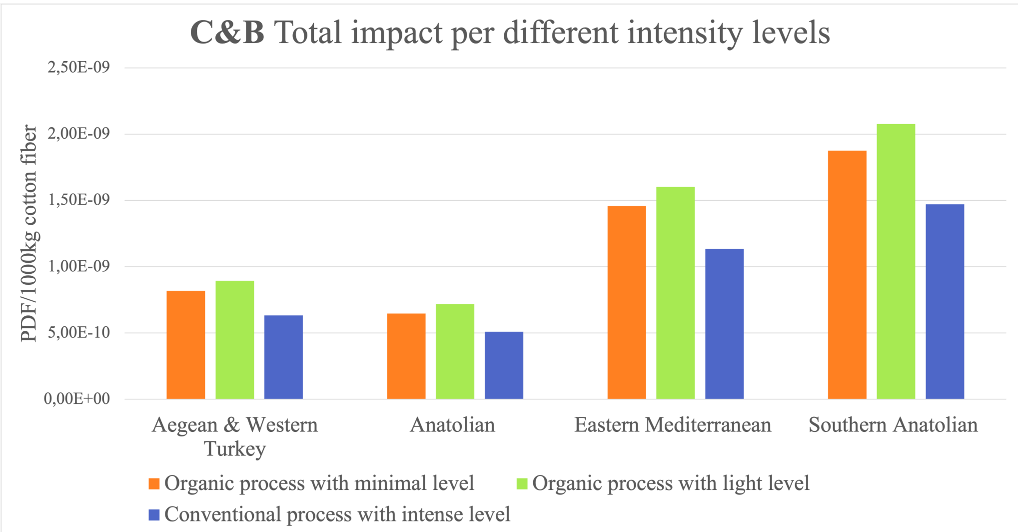


Figure 5.20: The C&B results with the addition of the organic cotton process calculated with the minimal intensity level.

The minimal intensity level forsters a lower impact, 9% lower than the light intensity level, meaning a difference of 25% between the intense and minimal compared to the 34% difference between light and intensive. This shows that the CF for the minimal intensity level assumes a lower impact than the light use. However, these results show that the difference in CFs following the intensity levels is inferior to the yield gap between conventional and organic cotton.

6
Discussion

The organic and conventional cotton production processes were calculated using the different LCIA models. The following chapter presents the discussion of the results, including sources of uncertainty and areas of future research in the study topics.

6.1 Discussion of results

When examining the total impact provided by ReCiPe2016, it is shown that conventional cotton has a higher cumulative impact. Land use substantially impacts both organic and conventional processes, but the effects of, primarily, toxicity, climate change, and water use contribute to the higher impact of conventional cotton. This relates to the primary process steps of concern in the conventional process, where toxicity is considerable in the fertilizer step, water depletion in the irrigation step, and land use in the cultivation. This result highlights the importance of considering multiple impacts, specifically impacts of fertilizer and pesticide use that have been mentioned to be lacking in LCAs of agricultural systems.

Land use has the highest impact in both processes based on the results of the ReciPe2016 model. All three models show that organic cotton has an approximately 35% higher impact, close to the yield variance between conventional and organic cotton, and a sensitivity analysis confirmed a roughly linear relationship between yield and impact in the model. Furthermore, the sensitivity analysis on adding land transformation showed the importance this might have on the final total impact. This emphasizes the yield's significance in assessing cotton production's environmental impact. However, uncertainties arise from the study's data sources as the conventional yield was not specific to Turkey, and the organic yield was based on total production over certified land. It is acknowledged that yield differences may vary depending on specific conventional and organic practices employed, and this emphasizes the need for data from the same region in future studies.

The study's findings highlight the significant environmental impact on biodiversity from using and producing artificial fertilizers. This suggests that reducing agrochemical usage is a viable means to mitigate conventional cotton's environmental impact. It must, however, be acknowledged that the emission models used for pesticide and fertilizer use emissions are highly simplified. This risks relatively broad assumptions for the calculation of emissions. So, for that reason, caution is urged when analyzing the results. Additionally, better models for emission levels and an examination of the reliability of the models would benefit the final result.

The cow manure used for fertilization was added to the system burden-free in organic cotton production. Animal husbandry, similar to agricultural practices, uses large amounts of land and might greatly impact biodiversity. Therefore, it would be interesting to examine how much the results would change if the impacts from animal husbandry, to an extent, were allocated to the manure.

Data uncertainty in the irrigation step is also a question of the reliability of the final results. Irrigation data was hard to find, and there was a significant variability among sources. Other models or methods for estimating irrigation amounts were not examined due to time constraints. This resulted in a difference in water use impact with a higher value in the conventional cotton, which is not necessarily accurate to real life. If the irrigation amounts for the two processes were the same, the endpoint impact from water use would probably be nearly the same, which might heavily impact the final difference between the two systems.

The effects and impacts of crop rotation, intercropping, and soil carbon levels were excluded from the study as they were deemed too challenging to consider within the time frame. Including it proved difficult due to uncertain assumptions and uncertainty surrounding how to implement it properly in LCA. These practices have been mentioned as an essential inclusion for a fair representation of organic agricultural practices and that an exclusion results in uncertainty and deviation from real-life differences (see section 2.7.1).

The exclusion of the construction of capital goods was potentially impactful when considering the final impacts. In an optimal study, the capital resources would be added but were excluded due to data difficulties and the similarity between the two. This breeds a level of uncertainty in terms of the actual total impact of the system. What difference this would have made is hard to say, but it is an uncertainty of the completeness of the study. Similarly, including all background processes in the C&B and HF would make sense to acquire a large-scale land use inclusion.

6.2 Discussion of models

The regionalization is a big difference between ReCiPe2016 and the land use models. Both C&B and HF derive their CFs from terrestrial ecoregions. In contrast, the current ReCiPe2016 model lacks differentiation between regions in the mid-to-end-point factors and instead relies on global species density values for impact assessment. While the comparison in regional species loss, as outlined in section 5.4, demonstrates ReCiPe2016's reasonably well-estimated average species loss value compared to C&B, it falls short in capturing the variability among ecoregions. Also, relying on a global species density appears overly simplistic for determining biodiversity impacts, particularly in land use.

Regionalization enables the incorporation of variables such as vulnerability or the risk of extinction, exemplified by VS and GEP in C&B and HF. This approach allows for recognizing that certain species within particular ecosystems may be more vulnerable to land use changes. However, implementing regionalization entails more sophisticated LCA calculations, increased reliance on well-acquired data, and heightened demand for transparency in global and international supply chains, which could pose challenges.

The difference in yield is a significant factor in comparing conventional and organic practices. Considering different land use intensity levels in LCAs is a possible measure to recognize the difference in how humans use the land and how that impacts biodiversity. Despite the C&B model's exploration of intensity levels, it did not overrule the yield variation between organic and conventional approaches. However, the study's outcomes reveal that incorporating multiple impacts addresses some distinctions in agricultural intensities.

Nevertheless, it is important to delve into the intended coverage of intensity categories within the C&B model. Currently, these categories represent a relatively small difference in value, and the aggregation into three intensity levels to encompass diverse cultivation types may be considered an oversimplification. Organic or low-intensity farming possesses several attributes that positively contribute to biodiversity. While practices such as crop rotation are mentioned to be included in the minimal intensity factors, all the intensity levels largely depend on land sparing, potentially overlooking the full potential of organic farming practices.

To comprehensively capture organic farming and foster incentives for its adoption, a shift towards a more inclusive approach is suggested. This may involve considering factors related to ecosystem multifunctionality or incorporating various aspects of ecosystem functioning. Such an approach could broaden the perspective beyond the discussion of yield trade-offs, value ecosystem functioning, and all ecosystem services that humans get from well-preserved nature, potentially promoting the benefits of organic cultivation. This could be accomplished by, for example, the exploration of functional diversity metrics in LCA as suggested by Ahmed et al. (2019) and de Souza et al. (2013).

The habitat fragmentation model represents a broader scope of biodiversity by acknowledging landscape fragmentation and associated effects. While the model, in the context of this study, does not exhibit higher impacts on biodiversity (with potential reasons outlined in section 5.4) or account for intensity factors, the inclusion of fragmentation effects remains essential.

It is intriguing to explore the potential use of the fragmentation model in LCAs of organic and conventional farming. Organic and agroecological farming integrates the natural ecosystem into human cropland use. If that, in turn, decreases fragmentation effects, it could be used as a distinction of agricultural intensity levels. Utilizing the fragmentation model may provide an opportunity to mirror applications emphasizing connectivity and dispersal possibilities in organic and conservation-based farming practices.

Although implementing such a strategy could introduce complexity to the model, it can potentially encourage adopting biodiversity-friendly agricultural practices and emphasize its positive aspects. In this context, a noteworthy development is a newly proposed model by Scherer et al. (Scherer et al., 2023), which combines the land use intensity model from C&B with the fragmentation model from HF. It has not been examined within the scope of this study but is recommended to be explored in future studies due to its combination of intensity levels and fragmentation effects.

Regarding the usability of the models, it is important to ensure that the land use models, C&B and HF, are operationalized or included in widely applied LCIA models to be more usable for practitioners. Even though the application of the land use models in this study did not prove overly complex, it would benefit in ensuring the adaptation of these models that they are added to models and software used in industry and research.

Finally, when discussing the models and their ability to capture impacts on biodiversity, it must be acknowledged that all models use the biodiversity indicator species loss when examining these impacts. This is merely one of several relevant biodiversity indicators, as presented by Noss et al. (NOSS, 1990). Using factors such as fragmentation and species dispersal in the HF, the analysis is placed on a landscape and species structure level, and the use of varying habitat affinity in all three models places it in a species composition level. However, these things still fail to cover all scopes of biodiversity.

6.3 Future research

Regarding future research, several key points would be interesting to analyze further. Firstly, examining the transition from conventional to organic cultivation through a consequential LCA would be interesting. This is to see both how the models translate in a consequential analysis and if it is possible to capture certain positive aspects of organic cotton cultivation better when examining the development from conventional to organic in a consequential LCA.

Secondly, as mentioned, ecosystem multifunctionality has an interesting potential for future development. Therefore, it would be important to perform the same study but add elements or models that consider more aspects of ecosystem multifunctionality.

Furthermore, there is much to be done regarding biodiversity in LCA. One crucial part is to ensure that impacts on biodiversity are covered in LCA and consistently examine the potential of standardizing the use of biodiversity in LCA and LCA in agricultural processes to ensure that all studies consider similar things and agree upon the significant essential points.

7 Conclusion

This study aimed to quantify the impacts on biodiversity from conventional and organic cotton fiber production in Turkey and how the systems differ. Furthermore, the study aimed to compare and assess three different LCIA models: ReCiPe2016, considering multiple biodiversity impacts, and C&B and HF, considering land use impacts. For the final conclusions, the focus will be brought back to the research questions.

What are the hotspots in the cotton textile production system in terms of impacts on biodiversity? Land use significantly affects both processes where the impact from the organic system is larger. Furthermore, toxicity, climate change, and water use are significant impacts of conventional cotton production, shedding light on fertilization use and production and irrigation.

How does the production of organic cotton differ from that of the conventional one in terms of impacts on biodiversity? Examining the cumulative impacts assessed by ReCiPe2016, conventional cotton has a larger environmental impact than organic cotton when considering multiple biodiversity impacts. The yield difference is a large factor in the difference between conventional and organic cotton, and the two land use models largely showed this difference.

What aspects of the models used are important to capture biodiversity impacts in organic and conventional cultivation processes, and how might they be lacking? The consideration of intensity levels, as seen in C&B, does not overrule the yield difference. Therefore, it is recommended to develop and include more models that consider factors of ecosystem multifunctionality to cover more aspects of biodiversity relevant to agriculture. Regarding the HF model, it would be interesting to examine the possibility of using fragmentation effects as an aspect of land use intensity.

Finally, in order to ensure that biodiversity impacts are included in all LCA, it is important to ensure that models aiming to better capture biodiversity impacts, such as C&B and HF, are implemented in operational models to enable their usability in industry and research. This is to make sure that the coverage and mitigation of damages to ecosystems are guaranteed in the development of technologies and products, ensuring that humans take responsibility towards the nature that carries them, enabling long-term sustainability.

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A

Appendix 1

A.1 Conventional Cotton

Table A.1: Data for the preparation and sowing step of conventional cotton

What	**Amount and Unit**	**Reference**	**Background Data Provider**
Inputs			
Cottonseeds	-	EcoInvent 3.9.1: *seed-cotton production, conventional - RoW - seed-cotton*	EcoInvent 3.8 *RoW: cottonseed production, for sowing*
Land	-	EcoInvent 3.9.1: *seed-cotton production, conventional - RoW - seed-cotton*	-
Diesel burned in Agricultural machinery	0.58MJ	Calculations based on information found in report by Nemcek & Kägi 2007	Diesel production (EU-28) GaBi
Transport of cottonseed from production to farm	1000km	Assumption	GaBi: *Truck Trailer 34-40 tonne 27t Euro 6*
Outputs			
Emissions from diesel combustion	-	Based on aggregated system in GaBi	

Table A.2: Data for the irrigation step of conventional cotton.

What	Amount and unit	Reference	Background Data Provider
Inputs			
Water	-	EcoInvent 3.9.1: *seed-cotton production, conventional - RoW - seed-cotton*	-
Electricity	0.64 MJ	Based on information from report by Nemcek & Kägi (2007)	GaBi *Turkey: Electricity grid mix 1-60 kilo volt (kV)*

Table A.3: Data for the fertilisation step of conventional cotton.

What	Amount and Unit	Reference	Background Data Provider
Inputs			
Fertilizers	-	Types and amount based on EcoInvent 3.9.1: *seed-cotton production, conventional - RoW - seed-cotton*	GaBi and EcoInvent background process datasets
Diesel burned in Agricultural machinery	-	Calculations based on information found in report by Nemcek & Kägi 2007	Diesel production (EU-28) GaBi
Transport of pesticides from production to farm	1000 km	Assumption	Gabi: *Truck Trailer 34-40t 27t Euro 6*
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	
Emissions from fertiliser use		Based on calculations by Nemecek et al. (2019	

Table A.4: Data for the spraying step of conventional cotton.

What	Amount and Unit	Reference	Background Data Provider
Inputs			
Pesticides	-	Types and amount based on EcoInvent 3.9.1: *seed-cotton production, conventional - RoW - seed-cotton*	EcoInvent 3.8: *Europe (RER): Pesticide production, unspecified*
Diesel burned in Agricultural machinery	-	Calculations based on information found in report by Nemcek & Kägi (2007)	GaBi: *Diesel production (EU-28)*
Transport of pesticides from pesticide production to farm	1000 km	Assumption	GaBi: *Truck Trailer 34-40t 27t Euro*
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	
Emissions from pesticide use		Based on calculations by Nemecek et al. (2019) and pesticide values found in the report by Kooistra et al. (2006)	

Table A.5: Data for the harvesting step of conventional cotton.

What	Amount	Reference	Background Data Provider
Inputs			
Diesel burned in Agricultural machinery	1.45 MJ	Calculations based on information found in report by Nemcek & Kägi (2007)	Diesel production (EU-28) GaBi
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	
Seed-cotton	1 kg		

A.2 Organic cotton

Table A.6: Data for the preparation and sowing step of organic cotton.

What	**Amount and Unit**	**Reference**	**Background Data Provider**
Inputs			
Cottonseeds	-	Ecoinvent 3.9.1: *seed-cotton production, organic - RoW - seed-cotton, organic,*	EcoInvent 3.8: *RoW: cottonseed production, for sowing, organic*
Land	0.000536 ha	Amount based on cotton yield (see 4.2.2)	-
Diesel burned in Agricultural machinery		Calculations based on information found in report by Nemcek & Kägi (2007)	GaBi: *Diesel production (EU-28)*
Transport of cottonseed from production to farm	1000 km	Assumption	Gabi: *TruckTrailer 34-40t 27t Euro 6*
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	

Table A.7: Data for the irrigation step of organic cotton.

What	**Amount and unit**	**Reference**	**Background Data Provider**
Inputs			
Water	-	Ecoinvent 3.9.1: *seed-cotton production, organic - RoW - seed-cotton, organic*	-
Electricity needed to pump the water	0.086 MJ	Calculations based on information found in report by Nemcek (Nemecek & Kägi, 2007)	GaBi: *Turkey: Electricity grid mix 1kV-60kV*

Table A.8: Data for the fertilisation step of organic cotton.

What	Amount and Unit	Reference	Background Data Provider
Inputs			
Cow dung	-	Ecoinvent 3.9.1:*seed-cotton production, organic - RoW - seed-cotton, organic*	
Diesel burned in Agricultural machinery	0.08 MJ	Calculations based on information found in report by Nemcek (Nemecek & Kägi, 2007)	GaBi: *Diesel production (EU-28)*
Transport of fertilizer from production to farm	1000 km	Assumption	GaBi: *TruckTrailer 34-40t 27t Euro 6*
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	
Emissions from fertiliser use		Based on calculations found in (Nemecek et al., 2019)	

Table A.9: Data for the harvesting step of organic cotton.

What	Amount and Unit	Reference	Background Data Provider
Inputs			
Diesel burned in Agricultural machinery	2.08 MJ	Calculations based on information found in report by Nemcek (Nemecek & Kägi, 2007)	GaBi: *Diesel production (EU-28)*
Outputs			
Emissions from diesel combustion		Based on aggregated system in GaBi	
Seed-cotton	1 kg		

The cotton ginning process is the same for both systems and is based on the EcoInvent dataset. This will not be presented here due to issues of license.

B
Appendix 2

Figure B.1: Total impact from the different ecoregions for different allocations of land transformation for conventional cotton using the C&B model.

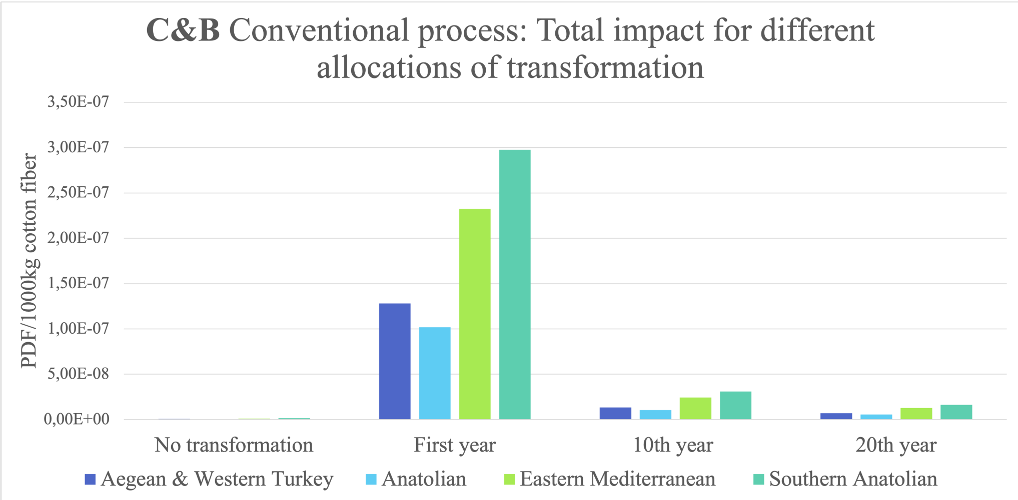


Figure B.2: Total impact from the different ecoregions for different allocations of land transformation for organic cotton using the C&B model.

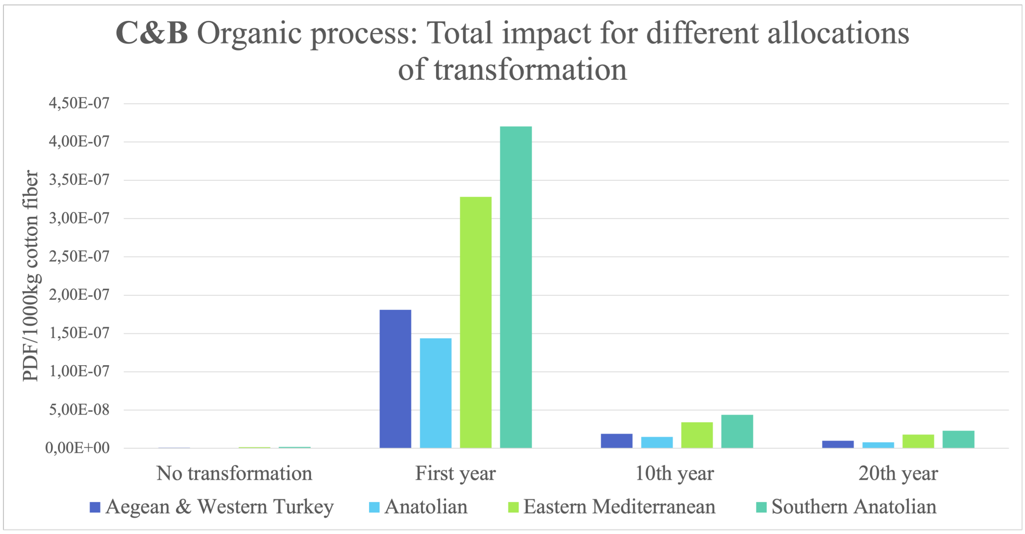


Figure B.3: Total impact from the different ecoregions for different allocations of land transformation for conventional cotton using the HF model.

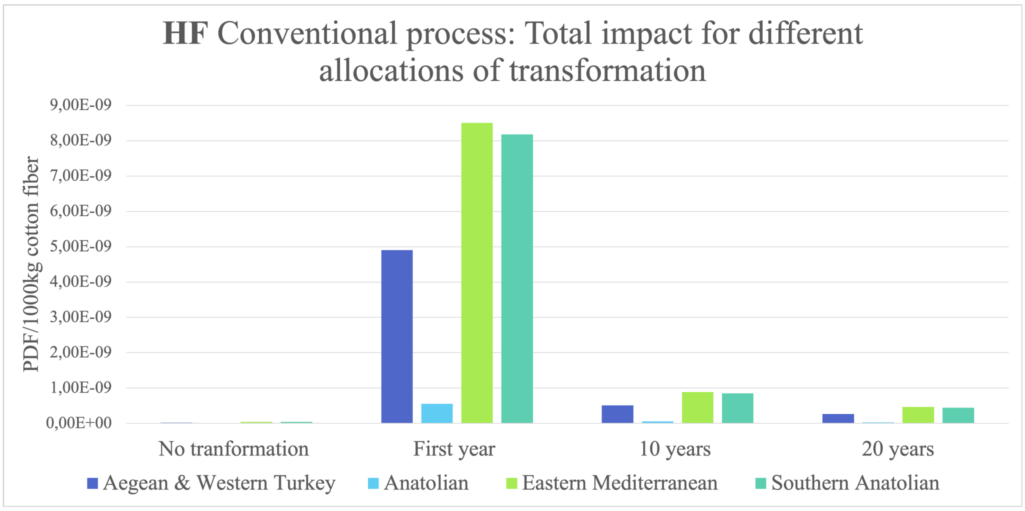
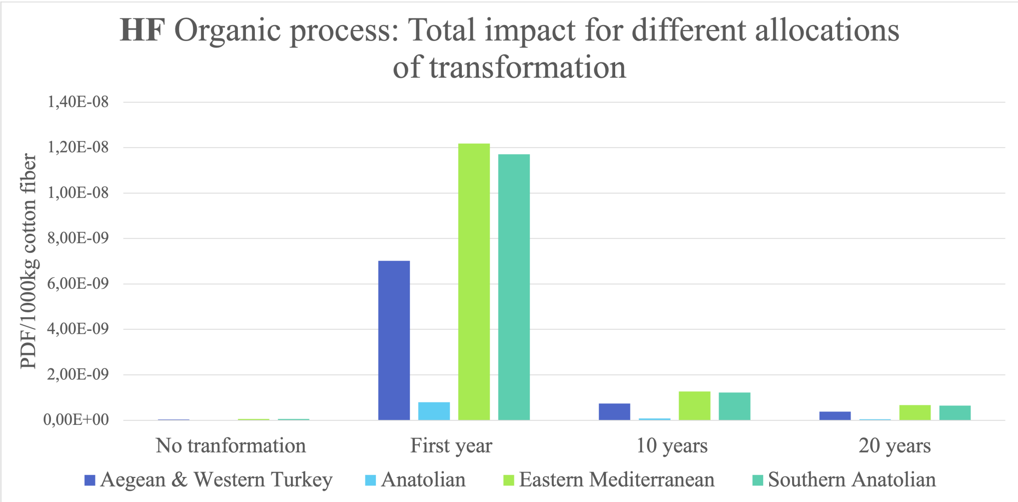


Figure B.4: Total impact from the different ecoregions for different allocations of land transformation for organic cotton using the HF model.



Production step	Preperation	Irrigation	Fertilisation	Spraying	Harvest	Ginning	Transport
Climate change (freshwater ecosystems)	1,81E-12	1,28E-11	2,1736E-11	2,1824E-12	2,3408E-12	4,6816E-12	1,2496E-12
Climate change (Terrestrial ecosystems)	6,65E-08	4,72E-07	7,964E-07	7,9904E-08	8,5536E-08	1,716E-07	4,5672E-08
Water use (Freshwater Ecosystems)	3,11E-11	5,92E-12	5,1128E-12	2,0504E-13	1,6896E-13	1,98E-12	1,1E-14
Water use (Terrestrial Ecosystems)	2,41E-07	2,48E-08	3,9688E-08	1,5752E-09	6,9608E-10	8,3072E-09	7,9904E-11
Freshwater ecotoxicity	1,16E-07	3,27E-12	2,3496E-06	2,8072E-07	2,5696E-11	1,1704E-12	2,2792E-12
Freshwater eutrophication	8,22E-09	1,07E-10	3,2384E-08	1,188E-08	4,9544E-10	3,5992E-11	8,1576E-11
Land use	1,56E-07	2,98E-08	8,2632E-08	7,8496E-09	9,856E-08	9,944E-09	1,7072E-08
Marine ecotoxicity	1,65E-08	4,18E-12	3,344E-07	3,8544E-08	1,1792E-11	1,4256E-12	9,24E-13
Marine eutrophication	2,68E-10	2,17E-12	4,6112E-11	1,8656E-11	6,2392E-12	7,2952E-13	1,0208E-12
Photochemical ozone formation	9,24E-09	5,15E-08	7,48E-08	1,012E-08	8,6592E-09	1,76E-08	1,936E-09
Terrestrial acidification	4,20E-08	3,67E-07	2,024E-07	5,1656E-08	1,7688E-08	1,232E-07	2,5872E-09
Terrestrial ecotoxicity	8,60E-07	6,85E-10	0,000017424	1,9976E-06	1,8568E-10	2,332E-10	1,5136E-11

Table B.1: The total impact of the conventional background process steps presented per impact category including transport.

Production step	Preparation	Irrigation	Fertilisation	Spraying	Harvest	Ginning
Climate change (Freshwater Ecosystems)	6,2832E-12	0	2,7016E-11	3,2472E-13	1,5664E-11	0
Climate change (Terrestrial Ecosystems)	2,2968E-07	0	9,856E-07	1,188E-08	5,7464E-07	0
Water use (Freshwater Ecosystems)	-6,336E-14	2,8864E-09	-9,856E-15	-3,2736E-15	-1,584E-13	0
Water use (Terrestrial Ecosystems)	-2,3496E-10	0,0000011616	-3,6432E-11	-1,2144E-11	-5,8696E-10	0
Freshwater ecotoxicity	-2,6752E-14	0	0,000000968	9,064E-09	-6,6792E-14	0
Freshwater eutrophication	-1,98E-10	0	6,9432E-08	-1,0208E-11	-4,9456E-10	0
Land use	0,00006072	0	-6,4152E-09	-2,1384E-09	-1,0296E-07	0
Marine ecotoxicity	2,288E-13	0	2,0064E-07	8,3776E-09	5,7112E-13	0
Marine eutrophication	-2,4112E-12	0	2,4728E-09	-1,2496E-13	-6,028E-12	0
Photochemical ozone formation	1,3904E-08	0	8,624E-08	7,2072E-10	3,4848E-08	0
Terrestrial acidification	1,0824E-08	0	2,8512E-06	5,5792E-10	2,6928E-08	0
Terrestrial ecotoxicity	4,972E-12	0	7,7088E-13	9,856E-09	1,2408E-11	0

Table B.2: The total impact of the conventional foreground process steps presented per impact category.

Production step	Preparation	Irrigation	Fertilisation	Harvest	Ginning	Transport
Climate change (freshwater ecosystems)	2,46E-13	2,35E-12	1,73E-13	4,51E-12	5,84E-12	3,89E-11
Climate change (Terrestrial ecosystems)	8,98E-09	8,60E-08	6,35E-09	1,65E-07	2,14E-07	1,43E-06
Water use (Freshwater Ecosystems)	1,75E-14	1,08E-12	1,26E-14	3,26E-13	2,68E-12	3,42E-13
Water use (Terrestrial Ecosystems)	8,34E-11	4,52E-09	5,17E-11	1,34E-09	1,13E-08	2,49E-09
Freshwater ecotoxicity	1,33E-08	5,97E-13	1,91E-12	4,95E-11	1,49E-12	7,11E-11
Freshwater eutrophication	4,37E-09	1,95E-11	3,68E-11	9,50E-10	4,86E-11	2,54E-09
Land use	7,33E-08	5,43E-09	7,32E-09	1,90E-07	1,35E-08	5,33E-07
Marine ecotoxicity	1,89E-09	7,63E-13	8,73E-13	2,26E-11	1,89E-12	2,88E-11
Marine eutrophication	2,15E-11	3,96E-13	4,64E-13	1,21E-11	9,86E-13	3,18E-11
Photochemical ozone formation	1,17E-09	9,42E-09	6,43E-10	1,67E-08	2,33E-08	6,04E-08
Terrestrial acidification	3,96E-09	6,70E-08	1,31E-09	3,41E-08	1,66E-07	8,07E-08
Terrestrial ecotoxicity	9,86E-08	1,25E-10	1,38E-11	3,57E-10	3,11E-10	4,72E-10

Table B.3: The total impact of the organic background process steps presented per impact category including transport.

Production step	Preparation	Irrigation	Fertilisation	Harvest	Ginning
Climate change (freshwater ecosystems)	1,35E-12	0,00E+00	3,02E-11	3,03E-11	0,00E+00
Climate change (Terrestrial ecosystems)	4,92E-08	0,00E+00	1,11E-06	1,11E-06	0,00E+00
Water use (Freshwater Ecosystems)	-1,36E-14	5,24E-10	-1,18E-14	-3,05E-13	0,00E+00
Water use (Terrestrial Ecosystems)	-5,02E-11	2,11E-06	-4,36E-11	-1,14E-09	0,00E+00
Freshwater ecotoxicity	-5,71E-15	0,00E+00	5,73E-09	-1,28E-13	0,00E+00
Freshwater eutrophication	-4,23E-11	0,00E+00	6,45E-08	-9,50E-10	0,00E+00
Land use	1,17E-04	0,00E+00	-7,67E-09	-1,99E-07	0,00E+00
Marine ecotoxicity	4,88E-14	0,00E+00	1,16E-09	1,10E-12	0,00E+00
Marine eutrophication	-5,16E-13	0,00E+00	4,78E-09	-1,16E-11	0,00E+00
Photochemical ozone formation	2,98E-09	0,00E+00	1,17E-07	6,71E-08	0,00E+00
Terrestrial acidification	2,31E-09	0,00E+00	1,68E-06	5,19E-08	0,00E+00
Terrestrial ecotoxicity	1,06E-12	0,00E+00	9,24E-13	2,39E-11	0,00E+00

Table B.4: The total impact of the organic foreground process steps presented per impact category.

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