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Incorporating Land Use Impacts on Biodiversity into Life Cycle Assessment for the Apparel Industry

A group project submitted in partial satisfaction of the requirements for the degree of
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The Group Project is required of all students in the Master of Environmental Science and Management (MESM) Program. The project is a three-quarter activity in which small groups of students conduct focused, interdisciplinary research on the scientific, management, and policy dimensions of a specific environmental issue. This Group Project Final Report is authored by MESM students and has been reviewed and approved by:

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Abstract

The significant amount of land used by the apparel industry contributes to a global decline in biodiversity. Although land use is a major driver of biodiversity loss, there is no easily applicable method for incorporating land use impacts on biodiversity into life cycle assessment (LCA), which means that biodiversity may be neglected in corporate sustainability decision-making. At the request of Patagonia, Inc., this study assesses an emerging model attempting to fill this gap. Published by de Baan et al. (2013b), the model provides a relatively complete set of biodiversity characterization factors, used to convert a quantity of occupied land into an absolute, regionally specific measure of potential species loss. We apply the model to four Patagonia t-shirts to quantify each product system's biodiversity impacts in order to evaluate operational limitations and opportunities for the model within the apparel industry. Although we find that high uncertainty and a broad land use classification scheme limit the utility of the model, we provide recommendations on how to utilize the information gleaned from this study to begin analyzing the biodiversity impact of apparel product systems. Primarily, we identify agricultural- and pastoral-based processes as primary contributors to biodiversity impact.

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Executive Summary

The global textile and apparel industry requires large inputs of land for raw material production and fabric manufacturing. Such land use has significant implications for biodiversity—the diversity of Earth's species, which provide critical services such as pollination, water purification, and climate regulation. With global biodiversity loss estimated at 30% over the last 40 years, the World Wide Fund for Nature (WWF) asserts that "the loss of biodiversity is, arguably, the greatest threat to stability and security today" (WWF 2014). Although land use is a major driver of this decline, there is no easily applicable and industry-wide method for incorporating land use impacts on biodiversity into life cycle assessment (LCA). Because LCA is a tool used across a range of industries for evaluating potential environmental impacts of a product system throughout its life cycle, the inability to easily include biodiversity loss alongside impacts such as climate change and water use may mean that companies are underestimating their environmental impacts, and neglecting biodiversity loss in their decision making. As a company at the frontier of sustainability, Patagonia commissioned this Bren Group Project to fill that gap so that Patagonia and other members of the apparel industry are able to make better-informed decisions and minimize their environmental impacts.

Working iteratively with Patagonia, we evolved the project to cover the following four objectives:

1. Review existing methodologies for incorporating land use impacts on biodiversity into LCA, and select a model with high potential for use within an apparel LCA
2. Quantify the potential land use impacts on biodiversity of four textiles by applying the selected land use impact assessment model to four Patagonia product systems
3. Evaluate the effectiveness of the new model for incorporating regional land use impacts on biodiversity into LCA, and identify limitations and areas of refinement

4. Assess the potential of this model for use by Patagonia and the apparel industry in evaluating its product life cycles

Upon review of existing land use LCA methodologies, we selected a promising model recently developed by de Baan et al. (2013b) based on the completeness and regional specificity of their published characterization factors for land occupation. Land occupation prevents the recovery of biodiversity from taking place due to human land use. Characterization factors provide a score that can be used to convert an input or output of a product system into a quantifiable impact particular to a specific impact category, such as biodiversity damage. In this case, the regional biodiversity characterization factors translate the quantity of land occupied for a process into an absolute measure of potential species loss based on its land use type (agriculture, pasture, urban, or managed forest) and ecoregion. Ecoregions are geographic units defined by patterns of climate, geology, and the evolutionary history of the planet, thus providing more ecologically relevant information than larger spatial scales such as biomes. The calculation combines an adapted version of the Species-Area Relationship (SAR) model, widely used in ecology to measure species loss, with the methodology outlined by a group of LCA experts in the paper "UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA." A similar set of characterization factors previously published by de Baan et al., measures a relative decrease in species richness between a particular land use type and a natural reference habitat at the spatial resolution of biomes (de Baan et al. 2013a). De Baan et al. (2013b) recommend using their updated, regional characterization factors to obtain an absolute, as opposed to relative quantification of biodiversity loss in terms of potential species extinction. De Baan et al. (2013b) assert that these newer characterization factors—those evaluated in this study—provide a more communicable, socially and politically relevant measure of biodiversity.

We used the regional biodiversity characterization factors to evaluate the biodiversity impact of four Patagonia t-shirts, made from cotton, wool, polyester, and lyocell, to compare the biodiversity impacts arising from the unique land use requirements of each textile. Primary data from Patagonia's suppliers, including property size, location, land use type, input requirements, and total output for each process used in manufacturing a particular t-shirt, were used to complete a life cycle inventory analysis (LCI) of each t-shirt. The LCI quantifies the amount of land occupied in m^2*years per functional unit for each unit process from raw material production through manufacturing. Our functional unit is one million t-shirts. The basic approach to calculating land occupation is the same across textiles: calculate how much land occupation a particular unit process requires to make one million t-shirts by multiplying the output per m^2 of each unit process by the inverse yield of every subsequent unit process. Each unit process is then assigned a characterization factor, as published by de Baan et al., based on its location and land use type. The land occupation and characterization factor are multiplied together to convert land occupation into an absolute measure of biodiversity loss. The result is a biodiversity impact (measured in potentially lost non-endemic species per functional unit) of each unit process, which can be summed to quantify the impact of the entire product system from cradle to factory gate.

We find that the textiles display a wide range of biodiversity impacts, with our results spanning five orders of magnitude. Taking our results at face value, we find that the production of one million wool t-shirts leads to the potential loss of roughly 4.8% of a non-endemic species regionally, while all other textiles produce a loss of less than 1%. The biodiversity impact of wool is approximately 20 times greater than cotton, 120 times greater than lyocell, and more than 9000 times greater than polyester. These results can be attributed to the low yield, and thus high land requirements, of wool grazing. However, the broad classification scheme used in the model may overestimate the negative biodiversity impact of Patagonia's wool, because it cannot capture the sustainable grazing strategies used by the t-shirt's suppliers. Additionally, we find that raw material production contributes more than 99% of the total biodiversity impact and land occupation for the cotton and wool t-shirts, and 92% of the lyocell t-shirt. These textiles require agriculture-, forest-, and pasture-based land uses, which have significantly lower yields, and thus require more land per unit, than the urban manufacturing processes. While the biodiversity impacts of cotton and wool manufacturing are dominated by the land occupation required for those processes, the impacts of polyester and lyocell are influenced by the characterization factors.

In its present form, the model is limited by four primary factors. First is the high uncertainty present in the characterization factors, as calculated by de Baan at al.; using characterization factors for the upper and lower bounds of a 95% confidence interval produces over a 100% change in the biodiversity impact of all evaluated textiles, and over 1700% change in the case of polyester. Second, the coarse land use classification means that users are unable to differentiate between land use management strategies, such as organic versus conventional cotton. Third, to take full advantage of the model requires location-specific knowledge of manufacturing processes, which may not be available to companies that rely on commodity products or lack transparency in their supply chains. Finally, one model may never be able to sufficiently quantify impacts on biodiversity, due to the complex nature of biodiversity. While these characterization factors essentially rely on species richness, or the number of species in a given area, the concept of biodiversity can also include species distribution, genetics, ecosystem functioning, and a range of other factors. Although this model has potential for future use in LCAs alongside other indicators, we find that currently it is better suited for providing generalizations about relative biodiversity impacts rather than for conducting discrete product system assessments. The continued refinement and development of methods for incorporating biodiversity impacts into LCA will greatly improve the ability of companies to make environmentally-informed decisions about product systems.

Definitions

Biodiversity
Biodiversity is the totality of genes, species and ecosystems of a region (Davis 2008). This term is often used to refer to genetic diversity, species diversity, and ecosystem diversity.

Biodiversity Impact
As used in this study, biodiversity impact is the result of the impact analysis, measured in potentially lost non-endemic species per functional unit. It is the biodiversity loss resulting from land occupation for human activities adjusted for the location and land use type of those activities.

Characterization Factor (CF)
Used in life cycle assessment, a characterization factor converts an assigned life cycle inventory analysis result to the common unit of the impact category indicator (ISO 2006E).

Ecoinvent
Ecoinvent is a professional database containing life cycle inventory data from a range of industries, such as data on energy supply, resource extraction, material supply, chemicals, metals, agriculture, waste management services and transport services that can be imported into life cycle assessment. It is developed and maintained by the Swiss Centre for Life Cycle Inventories.

Ecosystem Services
Ecosystem services are the benefits humans derive from wildlife and ecosystems, such as provisioning of food; regulation of climate and disease; support of the nutrient cycle and crop pollination; as well as cultural, spiritual and recreational benefits.

Elementary Flow
The material or energy of the studied system that has been drawn from the environment without previous human transformation, or the material or energy leaving the studied system that is released into the environment without subsequent human transformation (ISO 2006E).

Functional Unit

The functional unit is a pre-determined quantity of the product or service being evaluated in the life cycle assessment. It provides a basis for the comparison of performance between product systems.

GaBi

GaBi is a professional life cycle assessment modeling software developed and maintained by PE international. It integrates multiple databases to allow the user to develop a life cycle assessment model.

Impact Category

A class representing environmental issues of concern to which life cycle inventory analysis results may be assigned (ISO 2006E). The selected category represents the aspects of environmental impact that a life cycle assessment is interested in measuring. Classic impact categories include global warming potential, eutrophication, acidification, and human toxicity potential.

Impact Category Indicator

The impact category indicator is a quantifiable representation of an impact category (ISO 2006E). Each impact category has an indicator to characterize its impact.

Land Occupation

One of two types of land use interventions typically considered in life cycle assessment, land occupation is the continued use of land for human use, which prevents the land from recovering to a natural state (de Baan et al. 2013a).

Land Transformation

One of two types of land use interventions typically considered in life cycle assessment, land transformation, or land use change, alters the characteristics of a piece of land in order to make it suitable for a new use (Koellner 2013).

Life Cycle Assessment (LCA)

LCA is a method of compiling and evaluating “the inputs, outputs and the potential environmental impacts of a product system throughout its life cycle” (ISO 2006 E). It consists of four major phases: goal and scope definition, life cycle inventory analysis, life cycle impact assessment, and life cycle interpretation.

Life Cycle Impact Assessment (LCIA)

LCIA is the phase of LCA “aimed at understanding and evaluating the magnitude and significance of the potential environmental impacts for a product system throughout the life cycle of a product” (ISO 2006E). The results of the life cycle inventory analysis are assigned to particular areas of environmental concern, or impact categories.

Life Cycle Inventory Analyses (LCI)

LCI is the phase of LCA in which inputs and outputs of a product system are quantified through data collection and analysis (ISO 2006E).

1 Objectives & Significance

The textile and apparel industry is global and rapidly growing; American consumers alone spend $360 billion on clothes and shoes every year (AAFA 2014). Wool produced in the Patagonian grasslands of South America may be spun into yarn in China, sewn into a t-shirt in Vietnam, and worn by a consumer in the Unites States. The industry requires massive inputs of chemicals such as dyes and fertilizers, water, and energy, and contributes significantly to air and water pollution, climate change, and other environmental problems. In order to better understand and address the substantial impacts that the industry has on the quality of Earth's ecosystems, companies and researchers are using Life Cycle Assessment (LCA) as a tool to measure the potential environmental impacts of a particular product system throughout its life cycle—from raw material extraction to consumer use and product disposal.

While certain impacts, such as those to global warming, are readily incorporated into LCAs with standardized practices, methodologies for other impacts still need to be developed. In particular, there is currently no easily accessible and widely applicable LCA method for quantifying the impacts of land use on biodiversity—the diversity of Earth's species—even though land use is one of the major causes of biodiversity loss (de Baan 2013b). According to the World Wide Fund for Nature (WWF), "the loss of biodiversity is, arguably, the greatest threat to stability and security today." Although researchers estimate that there are roughly 8.7 million different species on Earth (Mora et al. 2011), global biodiversity has declined roughly 30% over the last 40 years (WWF 2014). Should biodiversity continue to decline at this rate, critical ecosystem services (services provided by the environment such as pollination, water purification, carbon sequestration, and soil formation) will be lost. Conversion of natural land for human use leads to decreased, modified, and fragmented habitats, in addition to degraded soil and water quality, and the exploitation of native species, all of which contribute considerably to biodiversity loss (Foley 2005). The inability to easily include biodiversity loss alongside impacts such as climate change and water use using LCA likely means that companies are underestimating their environmental impacts, and neglecting biodiversity loss in their decision making. Developing and propagating a method for incorporating land use impacts on biodiversity into LCA will increase awareness on the critical issue of global biodiversity decline, and enable companies to better minimize their environmental impacts.

Patagonia, Inc. (Patagonia), an outdoor apparel and gear company that has been a pioneer in sustainable manufacturing for more than 30 years, recognizes that they have a role to play in curtailing biodiversity loss, and are actively seeking ways to incorporate land use impacts into their life cycle assessments to make better-informed decisions. To this end, Patagonia commissioned a Bren Group Project to identify existing LCA land use impact methodologies, and pilot one of these methodologies using Patagonia's product supply chains to evaluate its effectiveness and make recommendations. Working iteratively with Patagonia, we evolved the project to cover the following four objectives:

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In addition to evaluating an emerging LCA methodology, this study provides Patagonia with a first-order assessment of the land use impacts of its common textiles, as well as a potential tool for future assessments. Because Patagonia does not own and operate its own manufacturing facilities, it is difficult to maintain complete visibility of its supply chain impact across the globe. By capturing data directly from the supply chain, this study will increase Patagonia's awareness of its global impacts, all the way down to its raw material suppliers and manufacturers. Patagonia can then apply this knowledge to inform decisions, and outline appropriate actions to take to minimize the impacts of its land use on biodiversity.

Furthermore, Patagonia has the ability to motivate industry-wide change in sustainability practices, so the significance of this project goes beyond assessing one company's impacts. Led by innovative companies such as Patagonia, the apparel industry is uniting through the Sustainable Apparel Coalition (SAC) to advance corporate sustainability efforts. The mission of the SAC is to create "a common approach for measuring and evaluating apparel and footwear product sustainability performance that will spotlight priorities for action and opportunities for technological innovation" (SAC 2014). Establishing a consistent measure for land use impacts on biodiversity is a critical addition to that common approach. Patagonia can use the SAC as a forum to share the findings of this study, and enable other companies to evaluate and reduce their own impacts on biodiversity.

2 Background

2.1 Life Cycle Assessment

Life Cycle Assessment (LCA) is a valuable tool used to evaluate the potential environmental impacts of a product system throughout its life cycle. As outlined in International Standard 14040 established by the International Standard Organization (ISO), LCA consists of four phases: Goal and Scope Definition, Life Cycle Inventory Analysis (LCI), Life Cycle Impact Assessment (LCIA), and Interpretation. LCA is an iterative process, with interpretation being conducted throughout to identify necessary adjustments in the goal, scope, and subsequent phases (ISO 2007).

At the core of an LCA is the *functional unit*, which quantifies the product(s) function(s) and serves as a common reference unit that enables comparison of results across equivalent product systems. In this study, the functional unit will allow us to compare the potential land use impacts of the four textile types we will be evaluating, each represented by a specific Patagonia t-shirt. The functional unit, as well as the *reference flow* (the amount of product(s) required to fulfill the intended function defined by the functional unit) and the *system boundary* are established in the first phase. During the LCI phase, inputs from and outputs to the environment, called *elementary flows*, of the product system are quantified through data collection (such as energy inputs, waste, emissions to air) and data calculation. In the LCIA, the results of the LCI are assigned to particular areas of environmental concern called *impact categories*, which are quantifiably represented by an *impact category indicator*. *Characterization factors* derived from a *characterization model* are used to convert the LCI results into *indicator results* summed for each impact category. In this way, the LCIA measures the potential environmental impacts of the specific inputs and outputs of the product system. For example, if CO_2 is an output in the LCI, it could be assigned to the impact category “global warming,” which might be represented by the category indicator "infrared radiative forcing," and converted using the characterization factor "Global Warming Potential" into a category indicator result represented in units of kg-CO_2-equivalent (ISO 2007). The LCA elements used in this study are summarized in Table 1.

Table 1. LCA elements used to complete this study

Impact Category	Potential Biodiversity Loss
Elementary Flow	Land occupation Unit: square meters * years per functional unit
Characterization Factors	Convert land occupation to regional biodiversity loss Unit: potentially lost non-endemic species for occupying one square meter for one year
Functional Unit	One million t-shirts
Indicator Result	Biodiversity Impact Unit: potentially lost non-endemic species per functional unit

2.2 Land Use in LCA

An international group of LCA experts recently completed the Land Use Life Cycle Impact Assessment (LULCIA) project (Koellner et al. 2013), which establishes an operational method for incorporating land use impacts on biodiversity and ecosystem services into LCA. The work of the LULCIA team is published in a Special Issue of the *International Journal of Life Cycle Assessment* called Global Land Use Impacts on Biodiversity and Ecosystem Services in LCA. The LULCIA initiative is one piece of the broader UNEP-SETAC International Life Cycle Initiative, a partnership formed by the United Nations Environment Programme (UNEP) and the Society for Environmental Toxicology and Chemistry (SETAC).

Our study drew heavily on the founding work of the UNEP-SETAC Life Cycle Initiative, as published in the article "UNEP-SETAC guideline on global land use impact assessment on biodiversity and ecosystem services in LCA" in the Special Issue of the *International Journal of Life Cycle Assessment.* This study establishes a framework for assessing impacts to biodiversity and ecosystems services as a result of land use. The UNEP-SETAC guideline identifies three land use interventions, which can be accounted for as elementary flows in the Life Cycle Inventory: land transformation, land occupation, and permanent impacts. Land transformation refers to a change in land use, such as conversion from forest to agriculture, while occupation is the ongoing use of a parcel of land, for example as an agricultural field, which prevents the land from returning to a natural state. Permanent impacts imply irreversible changes to the ecosystem (Koellner et al. 2013).

Building from the UNEP-SETAC guidelines, de Baan et al. developed a regional biodiversity characterization factor model, and calculated characterization factors for land occupation, transformation, and permanent impacts, as published in "Land use in life cycle assessment: global characterization factors based on regional and global potential species extinction" in the journal *Environmental Science and Technology* (de Baan et al. 2013b). Our study applies and evaluates the published regional biodiversity characterization factors for land occupation, which convert land occupation into the category indicator result measured in absolute units of "potentially lost non-endemic species," referred to throughout our results as biodiversity impact. Whereas de Baan et al. (2013a) previously published characterization factors for local, relative species losses, in the latest publication de Baan et al. (2013b) provide an absolute measure of biodiversity loss due to land use with impacts calculated at a regional scale. The previously published characterization factors measure a relative decrease in species richness between a particular land use type and a natural reference habitat at the broader spatial resolution of biome (de Baan et al. 2013a). These characterization factors are incorporated into the calculation of the new regional characterization factors as a species sensitivity factor, or relative decrease in species richness (see Eq. 4 in Appendix I). De Baan et al. (2013b) assert that the more recently published characterization factors, those used in this study, provide a more communicable, socially and politically relevant measure of biodiversity. De Baan et al. (2013b) recommend using their updated, regional characterization factors to obtain an absolute, as opposed to relative, quantification of biodiversity loss in terms of potential species extinction. Greater detail on the model used to generate these characterization factors is provided in Appendix I.

Finally, our study draws upon a case study conducted by Milà i Canals et al. (2012) of the land use impacts on biodiversity and ecosystem services of margarine in the United Kingdom and Germany. This article was also published in the Special Issue, and is one of the few available case studies demonstrating the potential applicability of the framework developed by the LULCIA initiative. The authors define their system boundary to exclude the distribution process and any processes downstream of it, but do include certain background impacts. The study uses seven different impact categories, including biodiversity damage potential, which was measured using the older set of local land occupation characterization factors developed by de Baan et al. (2013a), as well as transformation characterization factors calculated by the authors.

2.3 Measuring Biodiversity

Biodiversity is a complex and multi-faceted concept, which may be valued in many different ways. To complete a study considering biodiversity requires the complicated tasks of choosing an appropriate definition for biodiversity; selecting an appropriate indicator; and establishing the spatial resolution at which biodiversity is to be measured based on one’s objectives and data availability. Each of these decisions leads to certain tradeoffs.

2.3.1 Definition

The concept of biodiversity is intricate and pluralistic. Attempts to define the term have led to controversy among ecologists over whether “diversity” should be quantified with an absolute species count, or if “diversity” should also capture genetic diversity, species abundance and spatial distribution, functional elements within ecosystems, or the relative importance of a particular species to an ecosystem.

Franklin et al. (1981) recognized three attributes of biodiversity in a region: composition, structure, and function, together providing a comprehensive picture of a region's biodiversity. Although no single definition of biodiversity captures all of its integrated parts, and its measurement is dependent on the values and conservation priorities of the decision-maker (Faith 2008), one widely accepted definition of biodiversity is "the variety and variability among living organisms and the ecological complexes in which they occur" (OTA 1987). The characterization factors used in this study are based on the measurement of biodiversity using species richness, or the absolute count of different species within a particular area.

2.3.2 Indicator

Measurable indicators exist for the aforementioned biodiversity attributes for multiple levels of organization: regional landscape, community-ecosystem, population-species, and genetics (Noss 1990). Noss (1990) lists species richness as one appropriate indicator for assessing terrestrial biodiversity at the level of regional landscape. In the context of LCA, six potential biodiversity indicators related to species richness have been identified (summarized in Table 2): alpha diversity, Fisher's alpha, Shannon's entropy, Sorensen's S, and Mean Species Abundance (de Baan et al. 2013a). In their earlier calculation of local characterization factors of biodiversity impacts at the biome level, de Baan et al. (2013a) chose alpha diversity as their indicator due to its simplicity, data availability, and wide use. Although potential species extinction is used as the measure of biodiversity loss in the latest de Baan et al. (2013b) regional characterization factors, alpha diversity is incorporated through the "sensitivity of the species group to all land use types" variable (see Appendix I and Section 2.3.4 for more about this calculation). The species richness values in the characterization factors are taken from WWF and based on extant species ranges (de Baan et al. 2013b).

Table 2. Proposed Biodiversity Indicators, adapted from de Baan et al. (2013a)

Indicator	Measures	Data Requirements	Additional Information
Alpha Diversity	Species Richness	Species numbers	Gives equal weight to all species; highly dependent on sampling
Fisher's Alpha	Species Richness	Species numbers, total number of individuals	Corrects for incomplete sampling of Alpha Diversity
Shannon's entropy, H	Diversity	List of species, relative abundance	Reaches maximum when all species in a sample area are equally abundant
Sorensen's S	Dissimilarity	List of species	Values between 0 and 1
Mean Species Abundance	Abundance	List of current species, list of original species, relative abundance	Changes in abundance of each species between reference and current habitat

2.3.3 Spatial Scale

Biodiversity can be measured based on a number of spatial classifications, such as biomes, continents, and countries. The characterization factors calculated by de Baan et al. (2013b) consider biodiversity at the level of *ecoregions*, defined as "relatively large units of land containing a distinct assemblage of natural communities and species, with boundaries that approximate the original extent of natural communities prior to major land-use change" (Olson et al. 2001). Ecoregions take into account patterns of climate, geology, and the evolutionary history of the planet, thus providing more ecologically relevant results in these characterization factors than those previously developed using larger spatial scales such as biomes.

Olson et al., in conjunction with the World Wide Fund for Nature (WWF), utilized data from regional experts and biogeographic maps to breakdown 8 biogeographic regions and 14 biomes into 867 ecoregions. Through extensive exploration of regional systems by experts in each of the biomes, Olson et al. were able to adapt ecoregion boundaries from regional classification systems. Where widely accepted biogeographic maps were unavailable, Olson et al. used landform and vegetation information to develop ecoregion boundaries.

2.3.4 Modeling Biodiversity Loss

The species-area relationship (SAR) is widely used in ecology as an indirect means to predict species extinction due to habitat loss. The SAR model can be used to calculate the number of species in a new habitat area as a function of the number of species in the original habitat area (de Baan et al. 2013b). Some ecologists argue that estimating extinction based on the SAR method overestimates extinction rates by as much as 160% in some cases because the model assumes that "any loss whatsoever of population due to habitat loss commits a species to extinction," which is an oversimplification of how ecosystems function (He and Hubbell 2011), as species can persist on human-modified land (the "matrix"). Therefore, in calculating the characterization factors used by this study, de Baan et al. (2013b) use a matrix-calibrated SAR model developed by Koh & Ghazoul (2010) to measure species richness. The matrix SAR aims to correct for the shortcomings of the SAR model by adding terms that account for taxon-specific responses to individual components of the matrix and edge effects, thereby lowering predicted species extinction risk (de Baan et al. 2013b). A more detailed explanation of how this model was used to calculate the characterization factors used in this study is provided in Appendix I, while Appendix III provides a deeper look into the SAR.

2.4 Classifying Land Use Types

Despite the extensive list of global land use and land cover maps available, there is significant lack of agreement between specific types and locations of land cover and distribution. For this reason, de Baan et al. (2013b) delineate four broad land use categories. The land use types *agriculture*, *pasture*, *managed forest*, and *urban* are distinguished for each ecoregion based on two maps, the Land Degradation Assessment in Drylands (LADA, 1998-2008) and Anthromes (2000-2005) based on remote sensing and human statistics data (de Baan et al. 2013b). Although the earlier set of characterization factors by de Baan et al. (2013a) are regionalized at a coarser spatial resolution than the new set of characterization factors, they are based on a finer resolution land use classification system. For example, the land use activity "agriculture" in de Baan et al. (2013a) is further subdivided into arable and permanent crops, irrigated and non-irrigated, extensive and intensive, based on the Global Land Cover project (Bartholomé 2005) and the Global Biodiversity Model (Koellner et al. 2012). Unfortunately, due to lack of sufficient data across many land use categories, the previous set of characterization factors was far less complete than the newer set from de Baan et al. (2013b). Thus in choosing the new set of characterization factors, we lose the ability to distinguish between specific land use activities, in favor of a more complete set of regionally-specific characterization factors.

2.5 Assessed Products

In designing our study, we determined that using a life cycle assessment approach to calculate the biodiversity impact of land use for four textiles (wool, polyester, cotton, and lyocell) would prove most useful in fulfilling our project objectives, because these textiles can be expected to have markedly different impacts due to their unique land use requirements. In collaboration with Patagonia's representatives, we selected four Patagonia t-shirts of comparable weight and similar style, which each represent one of the four textiles evaluated in this study. The selected products and initial product data are described below for each material.

2.5.1 Cotton

Patagonia's Men's Sunset Logo T-shirt is used to represent cotton in this study. Patagonia uses only 100% organic cotton in all of their product lines (Patagonia 2013). Patagonia's cotton supply chain for this t-shirt consists of five unit processes. First, Texas Co-op, a farming cooperative in Texas, grows raw organic cotton, which is sent to a nearby ginning facility, where the cotton fiber is separated from the cottonseed, burrs, and trash. The cotton fiber represents approximately 80% of the profits from raw cotton, while cotton seed and other co-products account for 20% (Texas Co-op 2014). The ginned fiber is then spun into yarn at a facility in Mexico. An integrated facility in Mexico completes the remainder of the processes required to turn the yarn into a completed t-shirt, including knitting yarn into fabric, dyeing and finishing, and cutting and sewing the final t-shirt.

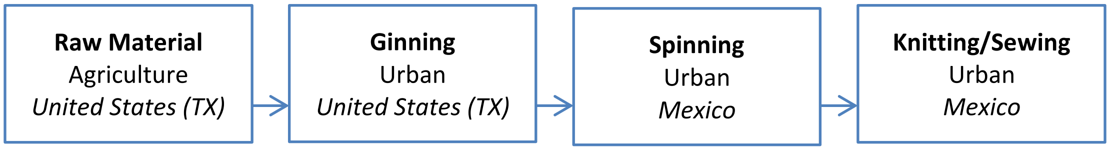


Figure 1. Process flow diagram of the cotton product system

2.5.2 Wool

The Women's Merino 1 Silkweight T-shirt represents wool. Although the t-shirt is made of 65% Merino wool and 35% Capilene, our inventory and calculations were completed as though the shirt were made from 100% wool based on available data and the objectives of the study. The wool for this shirt is supplied by Ovis XXI in Argentina. Patagonia has formed a partnership with Ovis XXI and The Nature Conservancy to utilize Grassland Regeneration and Sustainability Standard (GRASS) grazing practices, which are intended to restore natural grasslands in South America. More information about Patagonia's sustainable grazing partnership with Ovis XXI, the wool supplier, can be found in Section 5.1. With respect to Patagonia's supply chain, approximately 70% of the profits of sheep grazing come from wool production, while 30% come from the sale of sheep meat, or mutton (Ovis XXI 2014). The supply chain for this t-shirt consists of five unit processes, beginning with shearing sheep to produce raw fiber in Argentina. Another Argentine facility scours the wool to remove grease and dirt, then combs it to separate the longer fibers from the shorter fibers to create "top". Top is then sent to a spinning facility in China where it is turned into yarn, which is knitted into fabric in Thailand. Finally, the fabric is cut and the final t-shirt is sewn at a facility in Vietnam.

Figure 2. Process flow diagram of the wool product system

2.5.3 Polyester

Polyester is represented by the Men's Polarized Tee, made of 100% virgin polyester. Virgin polyester is a synthetic fiber derived from petroleum and natural gas. Six unit processes were assessed for Patagonia's polyester shirt, including raw material extraction, polymer to fiber production, spinning, knitting, cutting, and sewing. Patagonia's polyester polymers and staple fibers for this t-shirt are produced in South Carolina, then drawn (stretching the fiber) and spun into yarn at a plant in North Carolina. The yarn is knit into a fabric at a Los Angeles facility, where it is also dyed and finished. The final cutting and sewing of the shirt is done in El Salvador. Due to the nature of a commodity product such as petroleum, it is impossible to trace the specific origins of this product.

Figure 3. Process flow diagram of the polyester product system

2.5.4 Lyocell

Patagonia's lyocell, a cellulosic fiber that is part of the rayon family, is supplied by Lenzing AG under the brand Tencel®, and is represented by the Women's Necessity V-Neck. This shirt is made of 57% organic cotton and 43% lyocell. Tencel® is primarily made from the pulp of eucalyptus trees grown in South Africa, as well as beech and spruce trees grown in Europe. The wood is pulverized into a pulp at three different facilities in Austria, the Czech Republic, and South Africa. The pulp is processed into a fiber in Austria, as well as two facilities in the United Kingdom and Alabama. The fiber production is a closed loop cycle in which 99% of the primary chemicals used are recycled (Lenzing Aktiengesellschaft 2013). The fiber is then spun into yarn in Thailand, knitted, dyed, and finished in South Korea, and finally cut and sewn into the final product in Sri Lanka.

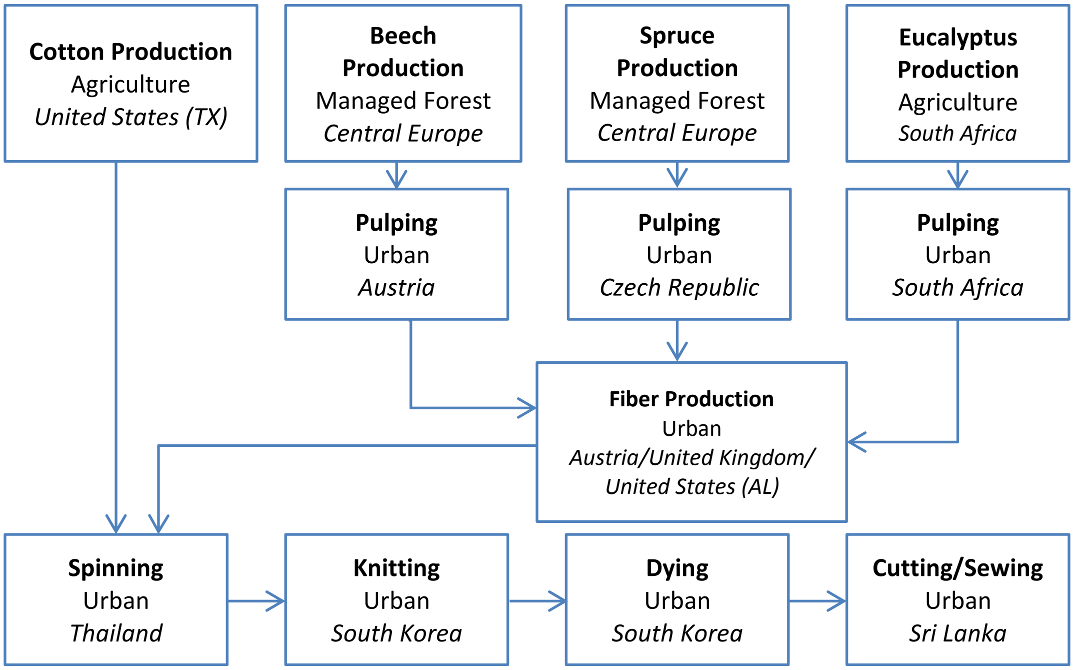


Figure 4. Process flow diagram of the lyocell product system

3 Methods

This case study seeks to quantify the impacts of land occupation on biodiversity using characterization factors developed by de Baan et al. (2013b). Figure 5 provides a conceptual overview of the study methods.

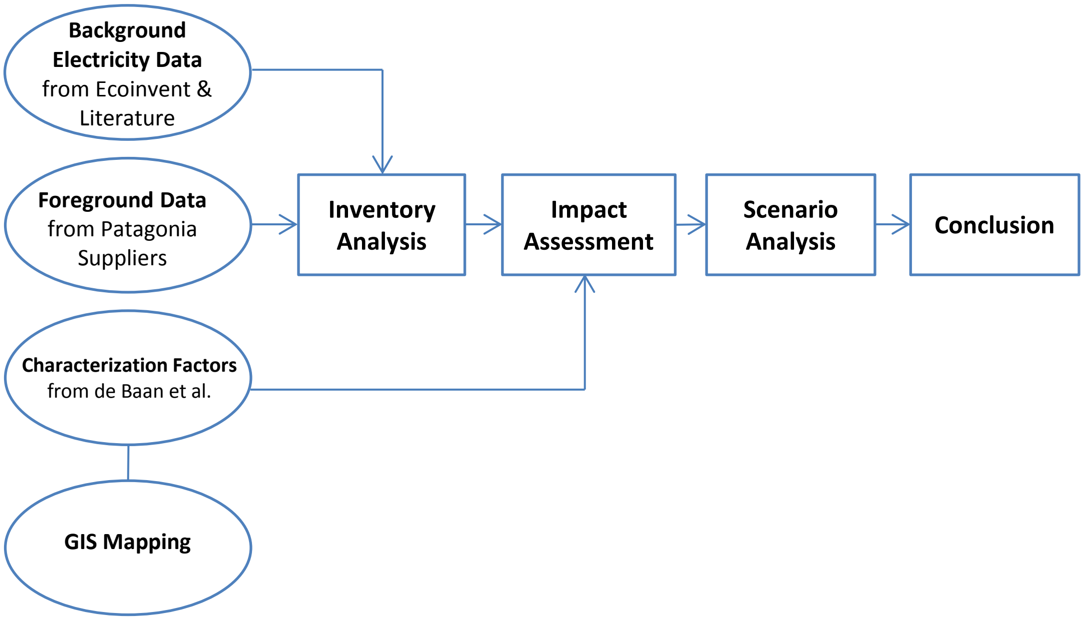


Figure 5. Conceptual overview of the study methods

In short, industry data and primary data from Patagonia's suppliers are combined in the life cycle inventory analysis (LCI) to calculate a land occupation inventory result for every unit process of each of the four textiles. In parallel, a characterization factor is assigned to each unit process based on its land use type and ecoregion, which was determined using GIS mapping. In the life cycle impact assessment (LCIA), the inventory results are combined with the assigned characterization factors to convert the LCI results into a measure of biodiversity loss due to land occupation. Scenario analyses were conducted to better understand the model, and to provide a deeper analysis of the results. To allow for the comparison of land use impacts of the four textiles of interest (wool, lyocell, cotton, and polyester) represented by Patagonia products, we defined the functional unit of this study as one million medium sized t-shirts. This value is a realistic approximation of an apparel company's annual product output. Because LCA is a linear model, the results can be easily scaled to any functional unit (e.g. one t-shirt or ten thousand).

3.1 Inventory Analysis

The life cycle inventory analysis (LCI), is the phase of a life cycle assessment involving the compilation and quantification of inputs and outputs for a given product system throughout its life cycle (ISO 2007). Using the primary data collected from Patagonia's suppliers, supplemented with secondary data, we calculated how much land occupation each unit process requires to manufacture one million t-shirts.

3.1.1 Data Collection

In order to collect primary data specific to each t-shirt supply chain, questionnaires were sent to Patagonia's suppliers soliciting data such as property size, facility size, location (address or coordinates), land use type, duration of land use, textile input requirements, total output, and yield. A sample questionnaire is shown in Appendix II.

Literature and the Ecoinvent 2.0 database were used to supplement any data that was unavailable through Patagonia's suppliers, such as the purified Terephthalic acid (PTA) and ethylene glycol inputs of polyester, as well as background electricity data. According to the Ecoinvent website, the database is "the world's leading supplier of consistent and transparent, up-to-date Life Cycle Inventory (LCI) data". Ecoinvent supplies information collected from a range of industries from agriculture to energy supply to packaging materials (Ecoinvent Centre 2014). It is one of the few databases containing land occupation elementary flows. The data provided in the Ecoinvent 2.0 database are mostly collected from companies in Europe. Specifically, we use Ecoinvent to supply data for land use requirements of amorphous PET, an input for the production of polyester fabric, and the background process of electricity.

3.1.2 Elementary Flows

The only elementary flow considered in our study is land occupation. Land occupation prevents the recovery of biodiversity from taking place due to human land use. Transformation and permanent impacts were determined to be beyond the scope of our study for several reasons. First, characterization factors for transformation and permanent impacts were unavailable during the scoping phase of our study. We therefore chose to focus our efforts on occupation impacts. Because Patagonia relies on suppliers with established facilities, the scope of our study focuses on the persistent impacts of its current operations rather than the impacts of land transformation that took place before Patagonia may have started sourcing their materials from these suppliers. Lastly, this study focuses on identifying the limitations of this impact model, and modeling occupation provided sufficient insight into the potential of the model. In the future it would be valuable to also model the reversible impacts caused as a result of land transformation, as well as permanent impacts from land occupation and transformation.

3.1.3 System Boundary

We established the system boundary of these four product systems as “cradle-to-factory gate” (Figure 6), thus including unit processes from raw material production through to the completed t-shirt. Because Patagonia’s t-shirts are treated relatively the same once they are manufactured, and because post-production processes are likely to have relatively low land occupation, the phases after the garment is shipped from the factory, such as distribution, use, and end-of-life, are excluded from the system.

To demonstrate the possibilities and limitations of applying the regional biodiversity characterization factors to background as well as foreground processes, we chose to include electricity in our system boundary as a representative background process. Application of the characterization factors to background processes presents several challenges: First, the geographical scope of the existing datasets has to be matched to the location of the actual process, which may or may not be known. Second, the scope of the land occupation measurements in the background datasets is likely to be different from what is measured in the foreground. Finally, the land occupation classes of the background datasets have to be matched to those used in the foreground. Although world average characterization factors are available, and can be used when a specific location is unknown, these reduce the resolution of the information to be gleaned using regional characterization factors. Additionally, the land use requirements for these processes are often unavailable, making the calculation of regional impacts impossible.

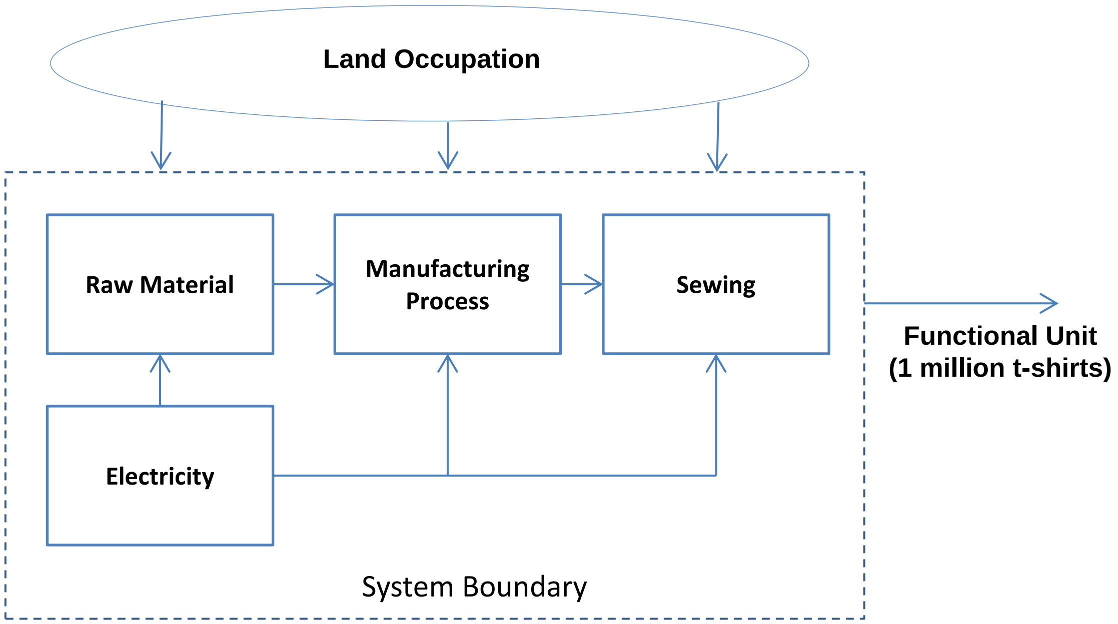


Figure 6. System boundary used in this case study

3.1.4 Calculating the Inventory Result

The basic approach to calculating land occupation, measured in m^2*years per functional unit, is the same across textiles: calculate how much land occupation a particular unit process requires to make one functional unit. To do so requires incorporating the inverse yields of each subsequent unit process to scale the land occupation requirements of the unit process in question. Using the inventory analysis of the cotton product system, we provide an example of how this calculation is done. The calculation is visualized in Figure 7.

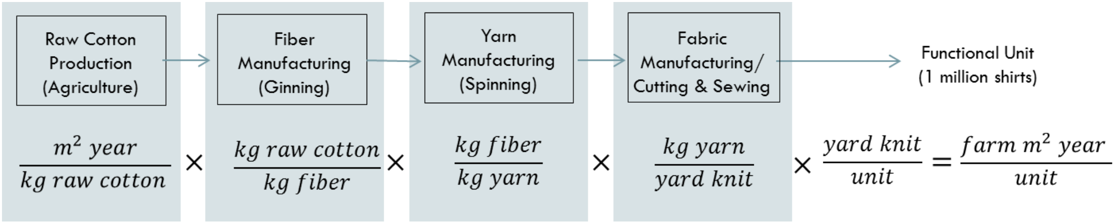


Figure 7. Example of the inventory analysis process for the cotton product system

First, we are interested in how much agricultural land is required to produce one functional unit. We divide the total property size by the annual amount of raw cotton it produces, and then multiply this number by the inverse yield (the amount of input over the output) of each subsequent unit process. In other words, the inverse yield tells us how many kilograms of fiber from the unit process “Ginning” are required to make a particular output of yarn from “Spinning”. For our calculation, the particular output of “Spinning” is the amount of yarn that is required to make a particular output of fabric from “Knitting”, and so on through to the sewing process where we divide the yards of knit fabric by the number of t-shirts produced at the sewing facility. The result of this multiplication is the land occupation for the raw cotton production unit process. We repeat this calculation for each of the unit processes. The total land occupation of the cotton t-shirt product system is the sum of the land occupations of every unit process. We used an inventory matrix to perform these calculations, which also allows us to easily scale our product system to any functional unit. Due to each textile’s unique features, additional manipulations of the data were required, as described in the following subsections.

Cotton

We were provided data for five cotton farms as a representative sample of the total thirty farms supplying organic cotton for the studied t-shirt. We therefore averaged the total size and total output, and thus yield, of these farms to be used for our inventory calculation. All of these farms were found to be within the same ecoregion. We have no reason to suspect that any one of these farms' size, output, or yield is more representative of the supplier's typical farm, and thus we determined that an un-weighted arithmetic mean was appropriate. Using the same reasoning, we also averaged the land use and outputs of the two ginners used to produce this t-shirt. Additionally, cotton farming produces burrs and cottonseed as economically valuable co-products of fiber production; we therefore allocated the land occupation accordingly. It was determined that an economic allocation would be more appropriate than a mass-based allocation, because the disproportionate masses of the co-products do not necessarily reflect the quantity of land being used for the unit process. An economic allocation attributes the land used in the process based on the product of interest's portion of the profits derived from the process. Patagonia's cotton supplier estimated that cotton lint accounts for 80% of the profits of raw cotton, thus we multiplied the land occupation by 80%. We then divided this by the total raw cotton fiber produced. We did the same for the total ginning property, because ginning is the process that separates the co-products.

Wool

Similar to cotton, Patagonia's suppliers provided us with data on nine pastures, which were reported to be representative of the forty-four pastures supplying the wool for the studied t-shirt. Therefore, we determined that using the arithmetic mean of these pastures' land use and outputs was appropriate. Three mills in the same ecoregion are used to perform the spinning process, so their land use and outputs were also averaged. Wool also has an economically valuable co-product: mutton, or sheep meat. The supplier estimated that 70% of the economic value derived from raising sheep is from the wool fiber. The economic allocation factor was thus applied to the raw material process by multiplying the total property size by 70% and dividing by the total wool output.

Polyester

The raw material inputs required for the production of polyester polymer, petroleum and natural gas, are commodity products, which means that location-specific data is unavailable. To approximate this data, a model of the processes leading up to polymer production was built in GaBi 6.0 (GaBi). GaBi is a professional software used widely in life cycle assessment to model product systems. Databases such as Ecoinvent are incorporated into GaBi to provide information collected from industry and science-based research on the inputs and outputs of particular product systems. Therefore, we were able to incorporate land occupation data from Ecoinvent with a model of the polymer production unit processes to supplement the missing data.

The process ‘polyethylene terephthalate, granulate, amorphous, at plant’ (PET amorphous) is used as the raw material for the polyester shirt. Any primary inputs were retrieved from the Ecoinvent database and linked to this raw material process. Using this Ecoinvent data, we determined that the unit processes for purified terephthalic acid (PTA) and ethylene glycol (EG) are the two major sources of land occupation flows. Using the Ecoinvent data, and the inventory calculation method described above, we were able to determine approximately how much land occupation the PTA and EG processes require to produce one functional unit. Although the Ecoinvent database reports land occupation for 21 specific categories, we excluded the categories of traffic area and water bodies, because these imply incorporating more aspects of land occupation than were included for other unit processes and textiles. We assigned the remaining 14 land occupation categories to one of the four land use types used in our study (agriculture, urban, pasture, and forest).

Lyocell

Calculating the impacts of lyocell was complicated by a few factors. First, the lyocell t-shirt is 57% organic cotton and 43% lyocell by weight. We used the data gathered for the organic cotton t-shirt to account for 57% of the fiber used to create the lyocell t-shirt. As discussed further in our results and discussion section, based on our initial findings for lyocell, we also completed calculations as though the shirt were made from 100% lyocell. Unless otherwise noted, the results and discussion presented in this paper refer to the 100% lyocell t-shirt. Second, the lyocell fiber is produced from three types of trees—beech, spruce, and eucalyptus, each of which is grown in a different region. Thus the raw material calculations had to be kept separate, and incorporated proportionally to their contribution to the t-shirt into the inventory calculation. The raw wood is pulped in three different countries—Austria, the Czech Republic, and South Africa, while fiber processing is done in Austria, the United Kingdom, and Alabama, so again the land occupation of the pulp and fiber had to be incorporated proportionally.

Electricity

Because we did not have primary energy use data, secondary data from literature and Ecoinvent were used to calculate results for electricity production. First, we used existing literature (Lenzing Aktiengesellschaft 2012; van der Velden et al. 2013) to determine how much electricity is used to produce a functional unit of each of the fabrics in our study, or where possible to produce a particular output of each unit process (e.g. 2.0 MJ electricity for raw fiber production per cotton t-shirt). Where a range of values was provided, we choose to use the higher electricity consumption data for our model. These values were limited to raw material production through fabric manufacturing due to lack of available data for subsequent processes. We feel it is reasonable to assume that later processes (finishing, cutting, and sewing) occupy similar amounts of land for electricity generation across textiles, and that these amounts will be small relative to the total land occupation of a particular textile.

Second, we selected electricity production processes from the Ecoinvent database to obtain a list of the land occupation requirements in m^2*years per MJ for each process. Each of these land occupations was then multiplied by the values we found for MJ per functional unit. Because production processes for most countries were unavailable in Ecoinvent, we used *US, electricity mix, agg, production mix* for unit processes in North and South America, *China, electricity mix, agg, production mix* for processes in Asia, and *RER, electricity mix, agg, production mix* for processes in Europe. We used the same process as for polyester raw materials to categorize the land occupation data provided by Ecoinvent. Due to the uneven availability of electricity data and the fact that electricity data were not provided in the same division of unit processes used in this study (e.g. raw material production through spinning might be aggregated in one number, or data for raw material production might be unavailable all together), our reported results do not include electricity unless otherwise noted. Electricity impacts as an example of background impacts were calculated separately and evaluated in relation to the foreground impacts.

3.2 Characterization Factors

In their electronic supplementary material, de Baan et al. (2013b) provide a table of their land occupation characterization factors. Each row contains the characterization factors for a particular ecoregion; there is also a set of World Average characterization factors. In each of the 867 ecoregions, there is one characterization factor for every land use type (agriculture, pasture, managed forest, and urban) for every taxonomic group (birds, mammals, reptiles, plants, and amphibians). There is also an aggregated characterization factor for every land use type, which was calculated based on a weighted average of all the characterization factors across taxonomic groups. The weighting factor of median species richness per taxa normalized by the median species richness of mammals was used to prevent plants, which have many more species recorded than other taxa, from dominating the results. We used this aggregated characterization factor to calculate our results, as overall species loss as opposed to species loss per taxa was our interest. We used the characterization factor table to assign a characterization factor to each unit process based on its ecoregion and land use type. A sample of the characterization factors used in this study is provided in Table 3.

Table 3. Examples of characterization factors used in this study. The unit for characterization factor is potentially lost non-endemic species for occupying one m^2 for one year

Characterization Factor	Ecoregion	Land Use Type	Unit Process
$1.44x10^{-10}$	West shortlands grass	Agriculture	Cotton raw production
$1.04x10^{-9}$	Southern Asia: Thailand	Urban	Wool knitting
$2.62x10^{-10}$	Southeastern mixed forests	Urban	Polyester fiber production
$2.46x10^{-10}$	Cantabrian mixed forests	Managed forest	Lyocell tree production
$5.56x10\text{-}^{11}$	Western European broadleaf forests	Urban	Lyocell tree pulping

3.2.1 Assigning Characterization Factors

It is important that inventory data be regionalized in the same manner as the characterization factors being used (de Baan et al. 2013b). Thus, in order to apply the characterization factors for measuring potential species extinction as done in our study, inventory data had to be properly matched up with the appropriate land use type, as well as the applicable regional classification, according to how the characterization factors were developed.

In order to determine the ecoregion in which the unit process takes place, the facility locations were converted to latitude and longitude coordinates, and overlaid onto the ecoregion map created by Olson et al. Because characterization factors are provided for four broad land use types, we assigned each unit process a land use type based on general knowledge (e.g. cotton farming is agriculture, wool grazing is pasture, and spinning is urban). Using the published table of regional biodiversity characterization factors (de Baan et al. 2013b) we then determined the characterization factor associated with that ecoregion and land use type. World average characterization factors were used for the polyester raw material and all background electricity calculations, because specific locations for these processes were unknown.

3.2.2 Adapting Characterization Factors

Because our final impact calculation requires one characterization factor, we had to create an adapted characterization factor for unit processes for which the ecoregion was unknown (e.g. we were provided with the source country, rather than an address) or which take place in multiple ecoregions. Characterization factors had to be adapted for the raw inputs of lyocell and wool.

Lyocell

For eucalyptus, beech, and spruce wood used in lyocell production, the supplier provided the source countries for each wood type, rather than a specific facility address. Each of these countries contains multiple ecoregions, and since ecoregions span political borders, it was necessary to aggregate the characterization factors accordingly. Specifically, beech and spruce are harvested from managed forests across central Europe, including the countries of Austria, the Czech Republic, Slovakia, Germany, Hungary, France, Belgium, Romania, Ukraine, Croatia, Bosnia, Slovenia, Belarus, and Switzerland. Eucalyptus is grown on plantations in eastern South African provinces and Swaziland, where it is a non-native species. Because the supplier, SAPPI, also produces pulp, paper, and chemical cellulose, it is impossible to identify the specific plantations providing the eucalyptus pulp used to produce the studied lyocell. A weighted characterization factor was created for each wood type based on the quantity of that wood sourced from each country listed as a supplier, as well as the portion of the beech-, spruce-, or eucalyptus-supplying ecoregion falling within those countries.

Using ArcGIS software, the ecoregion map created by Olson et al. was joined with a world countries map in order to calculate the percentage of each ecoregion in each country. By reviewing ecoregion descriptions, we determined which ecoregions grow the particular tree under consideration, and eliminated ecoregions that do not contain that tree from the map. Using Austria as an example, we found that three beech-containing ecoregions comprise 98.3% of the entire country, with the remaining 1.7% of the country occupied by ecoregions that do not contain beech (as shown in Figure 8, a map of beech-supplying ecoregions that fall at least partially into beech-supplying countries).

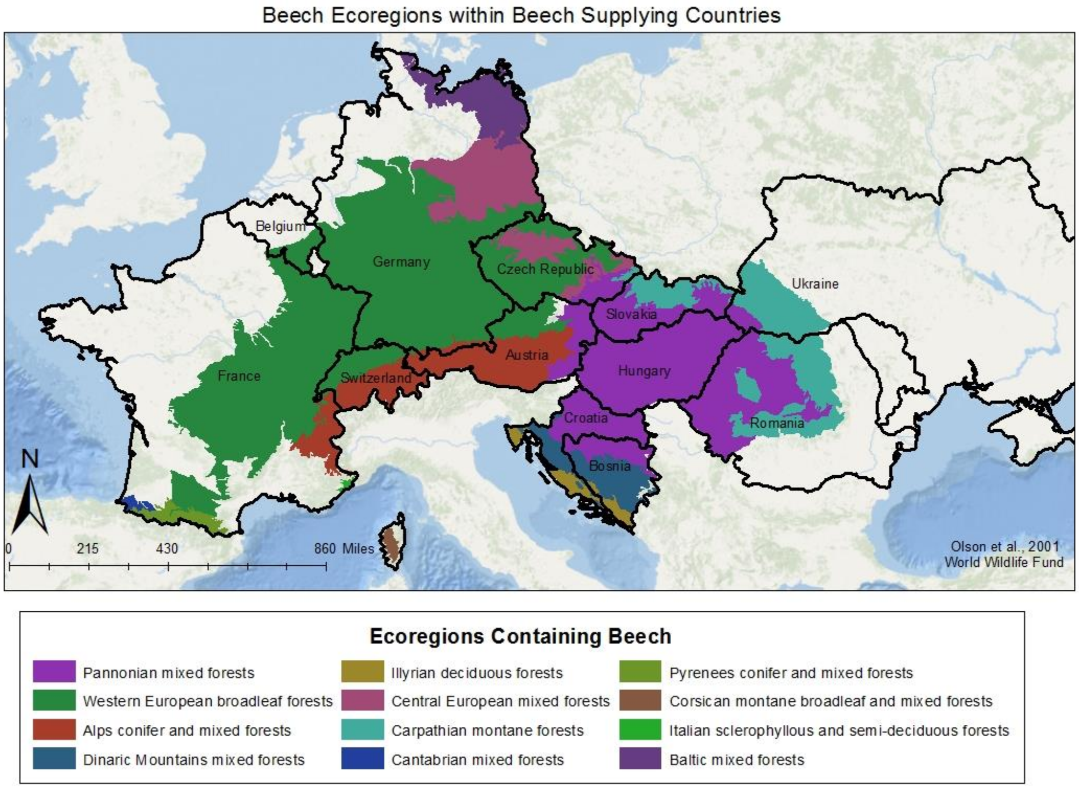
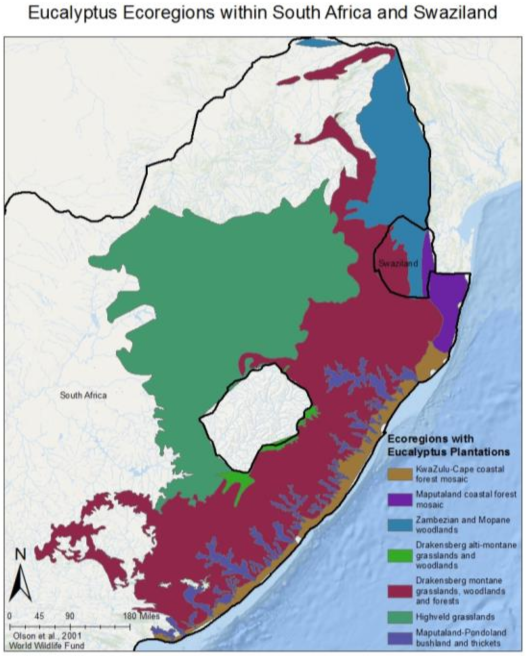


Figure 8. Countries that supply beech wood for lyocell production

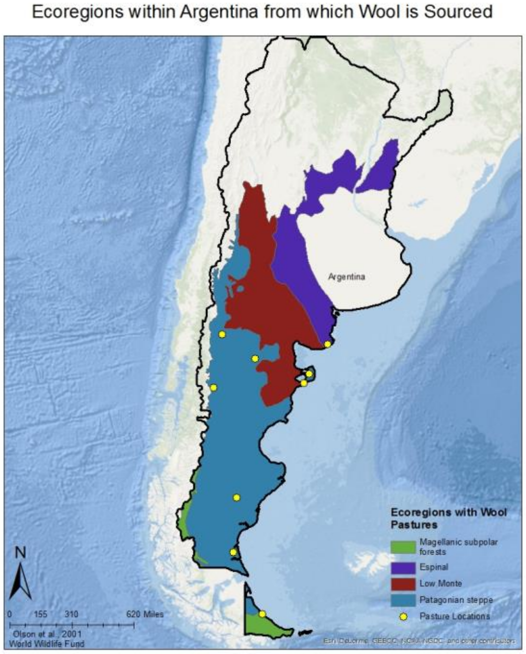
Next, a weighted average of beech-containing ecoregions was calculated for each country based on the portion of the ecoregion falling within that country. In Austria, the three beech ecoregions, Western European broadleaf forests, Pannonian mixed forests, and Alps conifer and mixed forests, make up 21.1%, 18.9%, and 58.3% of Austria's area, respectively. To account for the 1.7% of the country that does not grow any beech, we divided each of the aforementioned ecoregion percentages by 0.983 to find the portion of each beech-supplying ecoregion in the area of Austrian beech-growing ecoregions. Thus the make up of the potential beech-supplying area of Austria is 21.5% Western European broadleaf forests, 19.2% Pannonian mixed forests, and 59.3% Alps conifer and mixed forests. Each ecoregion's characterization factor was multiplied by its respective contribution to the beech growing area of Austria, and the results were summed to calculate a weighted characterization factor for Austria's beech harvesting. This weighted characterization factor was then multiplied by 50%, since 50% of beech used in lyocell production is sourced from Austria. This process was repeated to find a country-specific characterization factor for the other countries that supply beech. All country adapted characterization factors were added together according to the percentage of total beech they supplied, resulting in a single adapted characterization factor for the entire beech production unit process. Finally, these adapted country-specific characterization factors were used to find a single characterization factor for the entire production of each wood type, using a weighted average based on the percent contribution of that country to lyocell production. The same steps were repeated to develop a single characterization factor for the production of spruce.

For eucalyptus, the regions of Mpumalanga and KwaZulu Natal in South Africa and the entirety of Swaziland were given as locations for eucalyptus plantations. Any ecoregions falling at least partially within those areas were identified and included in a GIS map (Figure 9), with the exception of ecoregions in which eucalyptus plantations would be infeasible, such as mangroves. An average characterization factor was created for the remaining ecoregions, weighted based on the relative size of each ecoregion within the country.



Eucalyptus Ecoregions within South Africa and Swaziland

Figure 9. Countries and ecoregions that supply eucalyptus for lyocell production



Ecoregions within Argentina from which Wool is Sourced

Figure 10. Countries and ecoregions that supply wool

Wool

The wool used in the studied wool t-shirt is sourced from 44 pastures spread across southern Argentina. Representative data was provided for nine of these pastures, which are distributed across four ecoregions. Therefore, it was necessary to create a single, representative characterization factor from the unique characterization factors that corresponded to the four ecoregions supplying wool. The location of the pastures and the corresponding ecoregions can be seen in Figure 10. After identifying the characterization factors associated with each of the nine pastures, an average characterization factor was created, using a non-weighted arithmetic mean, to represent all forty-four source pastures.

3.3 Impact Assessment

In order to calculate regional impacts from land occupation, for each unit process, the land occupation inventory result (measured in m^2*years per functional unit) is multiplied by the characterization factor corresponding to the location and land use type of that unit process. The result is a biodiversity impact measured in potentially lost non-endemic species per functional unit. The total biodiversity impact is calculated for each unit process as shown in Equation 1,

$$BI_k = LO_k \times CF_{i,j} \qquad \text{Eq. 1}$$

where BI_k is the biodiversity impact of unit process k; LO_k is the land occupation in m^2*years per functional unit for unit process k; and $CF_{i,j}$ is the characterization factor for land use type i in ecoregion j. To calculate the total impact of the textile across the product system, the biodiversity impacts *(BI)* are summed (Equation 2).

$$Impact\ Result = \sum BI_k \qquad \text{Eq. 2}$$

Calculating the background impacts and polyester raw material impacts we use the same basic equation, but use different subscripts (Equation 3),

$$\sum_{n=1}^{n=14} BI_n = LO_n \times CF_{i,w} \qquad \text{Eq. 3}$$

where BI_n is the biodiversity impact of land occupation of one of the fourteen Ecoinvent land occupation categories; LO_n is the land use occupation of category n; and $CF_{i,w}$ is the world average characterization factor of the land use type of category i. Summing up the land use impact of all categories gives us the total background impact, or total polyester raw material impact. Background impacts can be summed with foreground impacts to get a total impact.

3.4 Scenario Analysis

After analyzing our initial results, we conducted scenario analyses to better understand the key drivers of our results and the effect of our assumptions. Because agricultural and pastoral unit processes proved to be significant contributors to total biodiversity impacts and total land occupation, we analyzed the effect of changing variables affecting those results, as described in the following subsections.

3.4.1 Hypothetical Change of Raw Material Source Location

For both cotton and wool we calculated a biodiversity impact of the t-shirt system based on a realistic change in the raw material sourcing location. Patagonia also sources wool from Australia, and primarily sources cotton from regions around Indore and Akola, India. For both scenarios, we were given broad regional sourcing locations, and thus had to create a single adapted characterization factor as was done for lyocell, described in Section 3.2.2. For wool, we used a straight average of the characterization factors for ecoregions which were likely to contain wool grazing operations, determined using the "Gridded Livestock of the World" (GLW), a distribution map of sheep and other livestock developed by FAO's Animal Production and Health Division in collaboration with the Environmental Research Group Oxford (FAO 2014). Similarly for cotton, ecoregions did not coincide directly with the Indian Provinces, and therefore characterization factors for the ecoregions present within sourcing provinces were averaged to produce a single characterization factor. In both scenarios, land occupation and data for processes subsequent to wool and cotton production were held the same as our original calculations, and a total biodiversity impact was calculated using our original method for both textiles.

3.4.2 Impact of Wool Sourcing Assumptions

Patagonia's suppliers provided us with data on only nine Ovis XXI pastures, which we were told were representative of all forty-four Ovis XXI operations. We assumed "representative" to include all aspects of the pastures including location and yield, as well as the contribution of each operation to Patagonia's wool t-shirt. In order to assess how this assumption might have affected our results, we recalculated our biodiversity impact for the entire product system nine times, each time using the raw material data from only one pasture. In this way, we were able to identify the lowest and highest impact operations, and provide a range for the possible impacts of the wool product system to reflect possible differences in distribution of pasture yield and location. We also took a straight average of the impacts generated by the nine farms when assessed individually, and evaluated how the results of this average differed from our initial results, in which we averaged yield and characterization factor rather than impact.

4 Results

4.1 Cotton

The results of our cotton inventory analysis and impact assessment are shown in Table 4. All characterization factors shown are the median, aggregated characterization factors for the particular land use type and ecoregion of the unit process. The total land occupation of the cotton t-shirt is 1.59×10^{7} m^{2}*years per functional unit. The total biodiversity impact of the cotton t-shirt is 2.29×10^{-3} potentially lost non-endemic species per functional unit. Nearly 100% of both the total land occupation and total impact of the cotton t-shirt comes from the raw material production unit process. The regional characterization factor for the spinning process is zero, because it is calculated using a local characterization factor for a desert biome where the dominant land use type, pasture, leads to potential species benefits. De Baan et al. (2013b) capped beneficial values at zero, thus the median species loss was assumed to be zero. As a result, the total biodiversity impact of spinning is also zero. As explained in Section 3.1.4 the displayed results for cotton, and the three subsequent textiles report foreground impacts only.

4.2 Wool

Table 5 shows that the total land occupation calculated in our wool inventory analysis is 1.77×10^{9} m^{2}*years per functional unit; the total biodiversity impact for the wool t-shirt is 4.75×10^{-2} potentially lost non-endemic species per functional unit. As in cotton, the characterization factors shown are the median, aggregated characterization factors. The raw material process contributes more than 99% of both the total land occupation and total biodiversity impact of the wool t-shirt.

4.3 Polyester

Table 6 displays the results of the polyester inventory analysis and impact assessment. Land occupation of the polyester t-shirt is 1.92×10^4 m^2*years per functional unit, and the biodiversity impact is 5.02×10^{-6} potentially lost non-endemic species per functional unit. A characterization factor for raw material production is not displayed, because as described in Section 3.1.4, world average characterization factors were combined with land occupation data from the Ecoinvent database to calculate the biodiversity impact. Unlike the other studied textiles, polyester's land use processes are all classified as urban land use types. Land occupation and biodiversity impacts of all unit processes are distributed fairly evenly, with the exception of spinning and finishing. Spinning contributes less than 5% of both total land occupation and total biodiversity impact; finishing contributes 3.06% and 8.11% respectively.

4.4 Lyocell

Cotton production in the cotton-lyocell blended t-shirt accounts for 94% of the total biodiversity impact, although it accounts for only half of the blended fiber by weight. Therefore, in order to look more closely at the impacts from beech, spruce, and eucalyptus, we conducted our analysis based on the results (Table 7) of modeling a 100% lyocell t-shirt. In doing so, we find that beech and eucalyptus are the two greatest contributors to both the t-shirt's total land occupation (9.77×10^5 m^2*years per functional unit) and total biodiversity impact (3.02×10^{-4} potentially lost non-endemic species per functional unit). Beech production contributes 68% of the total land occupation, but only 11% of the total biodiversity impact of the 100% lyocell t-shirt; eucalyptus production accounts for 30% of land occupation and 81% of the biodiversity impact. The characterization factor for eucalyptus production, which uses plantations and is thus classified as agriculture, is approximately 17 times greater than the characterization factor for beech, which is harvested from managed forests. The cutting and sewing unit process contributes an additional 7.5% to total biodiversity impact.

Table 4. Results of cotton inventory analysis (land occupation measured in m^{2}*years per functional unit) and impact assessment (biodiversity impact measured in potentially lost non-endemic species per functional unit)

	Cotton Production	**Fiber Production**	**Spinning**	**Knitting/ Sewing**	**Total**
Land Occupation	1.59x10^{7}	1.00x10^{3}	1.82x10^{2}	4.72x10^{3}	**1.59x10^{7}**
Percent of Total	*99.96%*	*0.01%*	*0.00%*	*0.03%*	
Character. Factor	1.44x10^{-10}	7.65x10^{-11}	0.00	4.86x10^{-10}	
Biodiversity Impact	**2.28x10^{-3}**	**7.67x10^{-8}**	**0.00**	**2.29x10^{-6}**	**2.29x10^{-3}**
Percent of Total	*99.90%*	*0.00%*	*0.00%*	*0.10%*	

Table 5. Results of wool inventory analysis (land occupation measured in m2*years per functional unit) and impact assessment (biodiversity impact measured in potentially lost non-endemic species per functional unit)

	Raw Wool Production	**Fiber Production**	**Spinning**	**Knitting/ Finish**	**Cutting/ Sewing**	**Total**
Land Occupation	1.77x10^{9}	2.85x10^{3}	1.09x10^{3}	4.39x10^{5}	1.55x10^{3}	**1.77x10^{9}**
Percent of Total	*99.97%*	*0.00%*	*0.00%*	*0.02%*	*0.00%*	
Character. Factor	2.66x10^{-11}	2.38x10^{-11}	1.13x10^{-10}	1.04x10^{-9}	1.67x10^{-10}	
Biodiversity Impact	**4.71x10^{-2}**	**6.77x10^{-8}**	**1.23x10^{-7}**	**4.58x10^{-4}**	**2.59x10^{-7}**	**4.75x10^{-2}**
Percent of Total	*99.04%*	*0.00%*	*0.00%*	*0.96%*	*0.00%*	

Table 6. Results of polyester inventory analysis (land occupation measured in m2*years per functional unit) and impact assessment (biodiversity measured in potentially lost non-endemic species per functional unit)

	Polymer Production	**Fiber Production**	**Spinning**	**Finishing**	**Cutting**	**Sewing**	**Total**
Land Occupation	7.53x10^{3}	3.56x10^{3}	8.38x10^{2}	5.88x10^{2}	2.63x10^{3}	4.07x10^{3}	**1.92x10^{4}**
Percent of Total	*39.20%*	*18.51%*	*4.36%*	*3.06%*	*13.69%*	*21.18%*	
Character. Factor	---	2.62E-10	1.14E-10	6.93E-10	4.17E-10	4.17E-10	
Biodiversity Impact	**7.95x10^{-7}**	**9.31x10^{-7}**	**9.51x10^{-8}**	**4.07x10^{-7}**	**1.10x10^{-6}**	**1.70x10^{-6}**	**5.02x10^{-6}**
Percent of Total	*15.83%*	*18.54%*	*1.89%*	*8.11%*	*21.83%*	*33.78%*	

Table 7. Results of lyocell inventory analysis (land occupation measured in m2*years per functional unit) and impact assessment (biodiversity measured in potentially lost non-endemic species per functional unit). Results from top continue into bottom table

	Raw Material Production			**Pulping**			**Fiber Production**		
	Beech	Spruce	Eucalyptus	Beech	Spruce	Eucalyptus	Austria	U.K.	U.S.
Land Occupation	6.62x10^{5}	1.86x10^{3}	2.90x10^{5}	3.12x10^{2}	2.24x10^{1}	1.80x10^{2}	2.19x10^{3}	3.16x10^{2}	2.06Ex10^{3}
Percent of Total	*67.76%*	*0.19%*	*29.67%*	*0.03%*	*0.00%*	*0.02%*	*0.22%*	*0.03%*	*0.21%*
Character. Factor	5.01x10^{-11}	6.48x10^{-11}	8.40x10^{-10}	5.56x10^{-11}	2.30x10^{-11}	4.56x10^{-9}	5.56x10^{-11}	1.20x10^{-11}	7.37x10^{-11}
Biodiversity Impact	**3.32x10^{-5}**	**1.20x10^{-7}**	**2.43x10^{-4}**	**1.73x10^{-8}**	**5.13x10^{-10}**	**8.22x10^{-7}**	**1.22x10^{-7}**	**3.79x10^{-9}**	**1.52x10^{-7}**
Percent of Total	*11.00%*	*0.04%*	*80.68%*	*0.01%*	*0.00%*	*0.27%*	*0.04%*	*0.00%*	*0.05%*

Table continued from above	**Spinning**	**Knitting**	**Finishing**	**Cutting/ Sewing**	**Total**
Land Occupation	1.23x10^{3}	6.40x10^{3}	9.96x10^{2}	9.56x10^{3}	9.77x10^{5}
Percent of Total	*0.13%*	*0.66%*	*0.10%*	*0.98%*	
Character. Factor	3.16x10^{-10}	1.39x10^{-10}	1.39x10^{-10}	2.35x10^{-9}	
Biodiversity Impact	**3.87x10^{-7}**	**8.88x10^{-7}**	**1.38x10^{-7}**	**2.24x10^{-5}**	**3.02x10^{-4}**
Percent of Total	*0.13%*	*0.29%*	*0.05%*	*7.44%*	

4.5 Background Impacts

As shown in Table 8, electricity production accounts for than less 1% of the total combined foreground plus background biodiversity impact for all textiles except polyester when calculated using a world average characterization factor. In polyester, electricity accounts for almost 75% of the total biodiversity impact. Land occupation ranges from 2.15×10^4 for cotton to 1.5×10^5 for polyester. Total biodiversity impact of electricity production ranges from 2.07×10^{-6} for cotton to 1.46×10^{-5} for polyester.

Table 8. Total land occupation and total biodiversity impact of electricity production for each t-shirt (land occupation in m^2* years per functional unit; biodiversity impact in potentially lost non-endemic species per functional unit). The bottom row displays the contribution of electricity's biodiversity impact to the total combined (foreground processes plus electricity) biodiversity impact of the product system

	Cotton	**Wool**	**Lyocell**	**Polyester**
Land Occupation for Electricity Production	2.15×10^4	4.62×10^4	2.57×10^4	1.5×10^5
Biodiversity Impact of Electricity Production	2.07×10^{-6}	4.38×10^{-6}	2.39×10^{-6}	1.46×10^{-5}
Foreground Biodiversity Impact	2.29×10^{-3}	4.75×10^{-2}	3.02×10^{-4}	5.02×10^{-6}
Contribution to Combined Foreground + Background Biodiversity Impact	*0.09%*	*0.01%*	*0.79%*	*74.45%*

4.6 Uncertainty Analysis

It is important to note in considering these results that de Baan et al. found high uncertainty when using Monte Carlo simulations to propagate parameter uncertainty into the characterization factors used in this study (de Baan et al. 2013b). De Baan et al. calculated characterization factors for the upper and lower bound of a 95% confidence interval (referred to within as High CF and Low CF, respectively), which we used to calculate the high and low biodiversity impacts of every unit process for each t-shirt. The results are shown Tables 7a, b, c, and d. For each unit process we calculated a high and low biodiversity impact value from the upper and lower bound characterization factors published by de Baan et al. (2013b), and then calculated the percent change of these new values from the biodiversity impact calculated using the median value characterization factor (reported in Sections 4.1-4.5).

In cotton, using high and low characterization factors, we found a 227% increase and a 186% decrease, respectively, in total biodiversity impact (Table 7a). The greatest change was a 1001% decrease in the biodiversity impact of the knitting and sewing unit process using the low characterization factor; the smallest change was a 185% decrease in the raw material production impact. As described in Section 4.1, values could not be calculated for spinning yarn unit process of the cotton t-shirt. For wool, the high characterization factor produced an increase in total biodiversity impact of 188%, while using the low characterization factor decreased the biodiversity impact of the t-shirt by 131% (Table 7b). The percent change using a high or low characterization factor ranged from 123% decrease (raw material production) to a 1907% increase (spinning), with the biggest changes occurring in spinning and fiber production. The total biodiversity impact for the polyester t-shirt increases by 959% using the upper bound confidence interval characterization factor and decreases 1353% using the low characterization factor (Table 7c). For the lyocell material, the total biodiversity impact increases by 240%, using the upper bound characterization factor, and decreases by 203% using the lower bound characterization factor. There was a large range in the percent change from using the high and low bound of the characterization factors. The range was between a 197% change and a 3888% change, which occurred in the lyocell fiber production process in the UK facility. Using the lower bound characterization factor for this facility decreased the biodiversity impact by two orders of magnitude (Table 7d).

The vast range across the textiles of percent change in biodiversity impact resulting from using either a high or low characterization factor is due to the equally large differences between the biodiversity impacts of the materials. Because polyester has a relatively small biodiversity impact, a change in the characterization factor due to uncertainty is going to be felt much more strongly than a change to the characterization factor for wool, which is miniscule relative to its land occupation.

Table 9a-9d. CF = characterization factor. Impact refers to biodiversity impact in potentially lost non-endemic species per functional unit. Median to High or Low % Change refers to the percent change of the biodiversity impact as calculated using the median CF versus the high or low 95% confidence interval CF

Table 9a. Results of cotton uncertainty analysis

	Cotton Production	**Fiber Production**	**Spinning**	**Knitting/ Sewing**	**Total**
Median CF	1.44x10^{-10}	7.65x10^{-11}	0	4.86x10^{-10}	
Median Impact	2.28x10^{-3}	7.67x10^{-8}	0	2.29x10^{-6}	2.29x10^{-3}
High CF	4.70x10^{-10}	5.07x10^{-10}	3.05x10^{-8}	3.35x10^{-9}	
High Impact	7.45x10^{-3}	5.08x10^{-7}	5.55x10^{-6}	1.58x10^{-5}	7.47x10^{-3}
Med. to High % Change	*226%*	*563%*	---	*590%*	***227%***
Low CF	-1.22x10^{-10}	-5.39x10^{-10}	-1.51x10^{-8}	-4.38x10^{-9}	
Low Impact	-1.93x10^{-3}	-5.41x10^{-7}	-2.74x10^{-6}	-2.06x10^{-5}	-1.95x10^{-3}
Med. to Low % Change	*-185%*	*-805%*	---	*-1001%*	***-186%***

Table 9b. Results of wool uncertainty analysis

	Wool Material	**Fiber Production**	**Spinning**	**Knitting/ Finish**	**Cutting/ Sewing**	**Total**
Median CF	2.66x10^{-11}	2.38x10^{-11}	1.13x10^{-10}	1.04x10^{-9}	1.67x10^{-10}	
Median Impact	4.71x10^{-2}	6.77x10^{-8}	1.23x10^{-7}	4.58x10^{-4}	2.59x10^{-7}	4.75x10^{-2}
High CF	7.58x10^{-11}	1.87x10^{-10}	1.27x10^{-9}	6.07x10^{-9}	9.59x10^{-10}	
High Impact	1.34x10^{-1}	5.33x10^{-7}	1.38x10^{-6}	2.66x10^{-3}	1.48x10^{-6}	1.37x10^{-1}
Med. to High % Change	*185%*	*688%*	*1023%*	*481%*	*474%*	***188%***
Low CF	-6.12x10^{-12}	-2.45x10^{-10}	-2.04x10^{-9}	-8.46x10^{-9}	-1.24x10^{-9}	
Low Impact	-1.08x10^{-2}	-6.97x10^{-7}	-2.23x10^{-6}	-3.71x10^{-3}	-1.91x10^{-6}	-1.45x10^{-2}
Med. to Low % Change	*-123%*	*-1130%*	*-1907%*	*-910%*	*-839%*	***-131%***

Table 9c. Results of polyester uncertainty analysis

	Polymer Production	**Fiber Production**	**Spinning**	**Finishing**	**Cutting**	**Sewing**	**Total**
Median CF	---	2.62x10^{-10}	1.14x10^{-10}	6.93x10^{-10}	4.17x10^{-10}	4.17x10^{-10}	
Median Impact	7.95x10^{-7}	9.31x10^{-7}	9.51x10^{-8}	4.07x10^{-07}	1.10x10^{-6}	1.70x10^{-6}	5.02x10^{-6}
High CF	1.24x10^{-9}	1.97x10^{-9}	1.17x10^{-9}	3.14x10^{-09}	5.08x10^{-9}	5.08x10^{-9}	
High Impact	9.33x10^{-6}	6.99x10^{-6}	9.83x10^{-7}	1.85x10^{-06}	1.34x10^{-5}	2.07x10^{-5}	5.32x10^{-5}
Med. to High % Change	*1073%*	*651%*	*933%*	*353%*	*1119%*	*1119%*	***959%***
Low CF	-1.22x10^{-9}	-1.49x10^{-9}	-1.29x10^{-9}	-1.24x10^{-9}	-6.96x10^{-9}	-6.96x10^{-9}	
Low Impact	-9.21x10^{-6}	-5.32x10^{-6}	-1.08x10^{-6}	-7.27x10^{-7}	-1.83x10^{-5}	-2.83x10^{-5}	-6.29x10^{-5}
Med. to Low % Change	*-1259%*	*-671%*	*-1236%*	*-278%*	*-1769%*	*-1769%*	***-1353%***

Table 9d. Results of 100% lyocell uncertainty analysis (results continue in table below)

	Raw Material Production			**Pulping**			**Fiber Production**		
	Beech	Spruce	Eucalyptus	Beech	Spruce	Eucalyptus	Austria	U.K.	U.S.
Median CF	5.01×10^{-11}	6.48×10^{-11}	8.40×10^{-10}	5.56×10^{-11}	2.30×10^{-11}	4.56×10^{-9}	5.56×10^{-11}	1.20×10^{-11}	7.37×10^{-11}
Median Impact	3.32×10^{-5}	1.20×10^{-6}	2.43×10^{-4}	1.73×10^{-8}	5.13×10^{-10}	8.22×10^{-7}	1.22×10^{-7}	3.79×10^{-9}	1.52×10^{-7}
High CF	7.15×10^{-10}	7.02×10^{-10}	2.50×10^{-9}	3.99×10^{-10}	2.67×10^{-10}	2.66×10^{-8}	3.99×10^{-10}	3.69×10^{-10}	1.09×10^{-9}
High Impact	4.74×10^{-4}	1.31×10^{-6}	7.24×10^{-6}	1.24×10^{-7}	5.97×10^{-9}	4.80×10^{-6}	8.75×10^{-7}	1.17×10^{-7}	2.25×10^{-6}
Med. to High % Change	1327%	983%	197%	618%	1064%	483%	618%	2984%	1380%
Low CF	-4.29×10^{-10}	-4.56×10^{-10}	-8.25×10^{-10}	-7.10×10^{-10}	-4.19×10^{-10}	-3.67×10^{-10}	-7.10×10^{-10}	-4.53×10^{-10}	-7.90×10^{-10}
Low Impact	-2.84×10^{-4}	-8.49×10^{-7}	-2.39×10^{-4}	-2.21×10^{-7}	-9.37×10^{-9}	-6.62×10^{-6}	-1.56×10^{-6}	-1.43×10^{-7}	-1.63×10^{-6}
Med. to Low % Change	-956%	-804%	-198%	-1378%	-1927%	-905%	-1378%	-3888%	-1172%

Table continued from above	**Spinning**	**Knitting**	**Finishing**	**Cutting/ Sewing**	**Total**
Median CF	3.16×10^{-11}	1.39×10^{-11}	1.39×10^{-11}	2.35×10^{-11}	
Median Impact	3.87×10^{-07}	8.88×10^{-07}	1.38×10^{-07}	2.24×10^{-05}	3.02×10^{-04}
High CF	2.00×10^{-09}	1.01×10^{-09}	1.01×10^{-09}	2.72×10^{-08}	
High Impact	2.45×10^{-06}	6.47×10^{-06}	1.01×10^{-06}	2.60×10^{-04}	1.48×10^{-03}
Median to High % Change	532%	629%	629%	1057%	389%
Low CF	-2.83×10^{-10}	-1.73×10^{-10}	-1.73×10^{-09}	-3.31×10^{-08}	
Low Impact	-3.47×10^{-06}	-1.11×10^{-05}	-1.73×10^{-06}	-3.16×10^{-04}	-8.67×10^{-04}
Median to Low % Change	-995%	-1348%	-1348%	-1510%	-387%

4.7 Scenario Analysis

4.7.1 Hypothetical Change of Raw Material Source Location

Wool

By changing only the sourcing location of the raw material process for the wool t-shirt (reflected by changing the characterization factor), we find the biodiversity impact of wool sourced from Australia to be 1,640% greater than wool sourced from Patagonia's suppliers in Argentina (bottom row of Table 10). In this analysis we assume that wool sourced from Australia has the same yield, and thus land occupation, as wool from Argentina. Realistically however, moving production to a new ecoregion would likely result in a change in yield due to different environmental conditions and operational strategies.

Table 10. Results of changing the sourcing location of wool from Argentina to Australia. Land occupation measured in m^2*years per functional unit; biodiversity impact is measured in potentially lost non-endemic species

	Argentine Wool	**Australian Wool**
Raw Material Land Occupation	1.77×10^9	1.77×10^9
Raw Material Characterization Factor	2.66×10^{-11}	4.63×10^{-10}
Raw Material Biodiversity Impact	0.047	0.820
Total Textile Biodiversity Impact	**0.048**	**0.818**
Raw Material Impact % Change from Argentine Wool		*1640%*
Total Textile Impact % Change from Argentine Wool		*1623%*

Cotton

Changing the location of cotton farming from Texas to India (results shown in Table 11), we find that the biodiversity impact for the raw material process increases by 71%. As with wool, the raw material process contributes over 99% of the biodiversity impact to the total. Therefore the total biodiversity impact from a t-shirt with cotton from India is 71% greater than that of a t-shirt with cotton produced in Texas. As with wool, we assume the yield of a cotton farm is the same in India as in Texas, though in reality they may be different.

Table 11. Results of changing the sourcing location of cotton from Texas to India. Land occupation measured in m^2*years per functional unit; biodiversity impact is measured in potentially lost non-endemic species

	Texas Cotton	**Indian Cotton**
Raw Material Land Occupation	1.59×10^{7}	1.59×10^{7}
Raw Material Characterization Factor	1.44×10^{-10}	2.47×10^{-10}
Raw Material Biodiversity Impact	2.28×10^{-3}	3.91×10^{-3}
Total Textile Biodiversity Impact	**2.29×10^{-3}**	**3.92×10^{-3}**
Raw Material Impact % Change from Texas cotton		*71%*
Total Textile Impact % Change from Texas cotton		*71%*

4.7.2 Testing Assumptions of Raw Wool Impact Assessment

The wool supplier provided data on nine grazing operations, which were labeled as “representative” of the forty-four total pastures that provide wool for this t-shirt. In the original impact assessment we assumed “representative” to be inclusive of yield and location distribution, and contribution of wool to Patagonia’s t-shirt. We thus used a straight average of the size, output, and characterization factor of each operation, essentially creating one unit process with a yield and characterization factor equivalent to the averages of those nine operations.

In order to test this assumption, we calculated the biodiversity impact per functional unit of the wool t-shirt for each of the nine grazing operations, as though the wool were sourced entirely from that grazing operation. Shown in Table 12, El Cronometro has the lowest operational impact while La Isabel has the highest operational impact in units of potentially lost non-endemic species per functional unit. We find that if the wool were sourced entirely from the operation with the highest impact, El Cronometro, the total biodiversity impact of 1 million wool t-shirts would increase by 258% to 0.17 potentially lost non-endemic species; if it were sourced entirely from the low impact operation, La Isabel, the impact would decrease by 60% to 0.019 potentially lost non-endemic species. The average biodiversity impact of the individual ranches is 0.0582 potentially lost non-endemic species, a 22% increase from our original calculation.

Table 12. Comparison of biodiversity impact results calculated for "high impact" and "low impact" grazing operations, El Cronometro and La Isabel, respectively, and using alternative averaging methods. Land occupation measured in m^2*years per functional unit; characterization factor measured in potentially lost non-endemic species per functional unit

Grazing Operation	Land Occupation	Characterization Factor	Biodiversity Impact
El Cronometro	$1.20x10^{9}$	$1.58Ex10^{-11}$	$1.90x10^{-2}$
La Isabel	$2.40x10^{9}$	$7.10x10^{-11}$	$1.70x10^{-1}$
Original Average	$1.77x10^{9}$	$2.66x10^{-11}$	$4.71x10^{-2}$
Scenario Average	Calculated individually for each grazing operation		$5.82x10^{-2}$

Recalculating our results using this alternative method provides additional useful information about this model, and gives us an upper and lower bound for what the biodiversity impact of wool could possibly be, based on available data. Regardless of our calculation method, the impact of wool is still two orders of magnitude greater than the textile with the next largest impact. This analysis also indicates the importance of accurate, specific data for using this model to calculate absolute results. To draw conclusions about the relative impacts of these textiles, a straight average based on limited data is sufficient; however, if a company wanted to use such data to make a sourcing decision about wool, it would be beneficial to solicit greater detail from potential suppliers about how much wool is supplied to their t-shirts by each operation, as well as the exact location and yield of all sourcing operations. The wool product system is particularly sensitive to assumptions because the operations are located in different ecoregions, and thus assigned different characterization factors.

5 Discussion

5.1 Wide Range of Biodiversity Impacts and Land Occupation

We find that the biodiversity impacts and land occupation of the four textiles are separated by orders of magnitude. Taking our results at face value, we find that the production of one million wool t-shirts leads to the potential loss of roughly 4.8% of a non-endemic species regionally, while all other textiles produce a loss of less than 1%. The total biodiversity impact of wool is 21 times greater than cotton, 157 times greater than lyocell, and more than 9,000 times greater than polyester, as shown in the bottom row of Table 13. Total land occupation for the four textiles is similarly distributed, spanning nearly 5 acres for polyester to over 437,000 acres in the case of wool, ultimately responsible for the wide range of total biodiversity impacts among the four textiles. The sheer magnitude of land occupation required for agriculture and pasture dwarfs the influence of location and land use type as captured by the characterization factor.

Table 13. Total land occupation (m^2*years per functional unit) and biodiversity impact (potentially lost non-endemic species per functional unit) per textile and ratio of each textile to wool, the textile with the greatest biodiversity impact

	Wool	Cotton	Lyocell	Polyester
Total Land Occupation	$1.77\text{x}10^9$	$1.5\text{x}10^7$	$9.77\text{x}10^5$	$1.92\text{x}10^4$
Biodiversity Impact	0.04751	0.00229	0.00030	0.00001
Ratio Textile to Wool	1:1	1:21	1:157	1:9461

While this range of values is interesting, three important points should be made. First, from the perspective of our client, other apparel companies, and their customers, these four textiles serve different functions and are not necessarily exchangeable. Therefore, looking across materials may not be particularly useful to a company making decisions about its products—while Patagonia would like to minimize the impact of its cotton t-shirts, and could thus compare two cotton product systems, it would not replace its cotton shirts with polyester, because the two textiles serve different purposes. Second, biodiversity loss is only one of many environmental impacts to which t-shirt production contributes, and a textile with a low impact to biodiversity loss from its land use may have a large impact with regards to greenhouse gas emissions, water requirements, or other impacts. Third, the broad classification scheme used in this model likely overestimates the biodiversity impact of wool (as well as other materials potentially), while the high uncertainty of the characterization factors is carried over into our results. The wool supplied for this t-shirt is sourced from a 40 million acre restoration effort between Ovis XXI, The Nature Conservancy, and the Savory Institute, which is intended to restore biodiversity by using a land management strategy that reverses the desertification of native grasslands due to human mismanagement of livestock (Savory Institute 2012). Sheep are moved between pastures, rather than grazing continuously on one plot of land, which reduces pressure on the landscape. However, because the assessed model uses only four broad land use types, classifying wool production as "pasture" does not capture the sustainable grazing strategies used by the t-shirt's wool suppliers.

5.2 Importance of Raw Material Production

Raw material production contributes more than 99% of the total biodiversity impact of the cotton and wool t-shirts, and 94% of the total biodiversity impact of the lyocell t-shirt. For polyester, which is produced using entirely urban classified land use types, this contribution is only 16%. This high contribution of the raw material process is due to the low yield, and thus large land occupation, of the agriculture, pasture, and managed forest land use types required for producing cotton, wool, and tree pulp relative to the minimal land occupation required for all subsequent, urban-based manufacturing processes.

5.3 Influence of the Characterization Factors

Although raw material land occupation dominates the total biodiversity impact for the cotton, wool, and lyocell t-shirts, location and land use type as captured by the characterization factors do influence outcomes. The role of the characterization factor in relative biodiversity impact can be seen particularly in lyocell raw material production, throughout the polyester product system, and in our scenario analysis of wool raw material production. Although the land use type plays a role in determining the characterization factor, companies using this model will have a limited ability to change the land use type associated with product production. Lyocell is an example of a product for which a company does have some control over land use type, as cellulose could be sourced from either managed forests or plantations (classified as agriculture).

Lyocell

Looking more closely at the dominant lyocell unit processes (eucalyptus and beech production), we find that although beech makes up only 38% (by weight) of the pulp mix used for Patagonia's lyocell, it contributes 68% of the total land occupation, which indicates that beech requires more land per ton dry output. In fact, beech requires about 3.5 times more land than eucalyptus to produce the same weight of dry output (shown in Table 14). However, we find that these higher land requirements are offset by the characterization factors.

Table 14. Comparison of biodiversity impact in potentially lost non-endemic species for producing one oven-dried ton of beech or eucalyptus, and corresponding characterization factors in potentially lost non-endemic species for occupying 1 m^2 for 1 year. CF=characterization factor

	Beech Production	**Eucalyptus Production (Actual)**	**Eucalyptus Production (Modified)**
Land use type of CF used	Managed Forest	Agriculture	Managed Forest
Annual yield (odt/m^2)	0.00034	0.00120	0.00120
Land occupation (m^2/odt)	2,940	833	833
Characterization factor	5.01×10^{-11}	8.40×10^{-10}	3.72×10^{-10}
Biodiversity impact	1.47×10^{-11}	7.00×10^{-11}	3.10×10^{-11}

Because the eucalyptus used in Patagonia's lyocell is harvested from plantations, it is classified as an agricultural land use, while beech is considered managed forest; eucalyptus is sourced from South Africa, and beech is sourced from Central Europe. If land occupation alone were driving the biodiversity impact, we would expect beech to have a correspondingly higher impact than eucalyptus. Instead, our results indicate that the biodiversity impact of eucalyptus per oven dried ton is 4.75 times greater than that of beech (Table 14). To understand whether this discrepancy arises from the land use type or the location component of the characterization factor, we compared the impact eucalyptus production would have if classified as managed forest instead of agriculture. Changing the land use type of the characterization factor for eucalyptus, but maintaining its same ecoregion, we found that the impact was still 2.26 times greater than that of beech (Table 14). This implies that the more intensive agricultural land use of eucalyptus, in addition to its more sensitive sourcing region, is influencing the biodiversity impact. Modifying the land use type without changing the location or yield is purely hypothetical, as in practice plantation tree farming is going to have a higher yield than a managed forest, and eucalyptus may not be harvested from managed forests in South Africa.

Polyester

As shown in Figure 11, the total land occupation and total biodiversity impact of polyester are distributed much more evenly across the unit processes, all of which are classified as an urban land use type, unlike the other textiles which require agriculture and pasture. If the characterization factors did not influence biodiversity impact, we would expect the two series in Figure 11 (contribution of the unit process to total biodiversity impact and contribution of the unit process to land occupation) to follow the same pattern. However, we see that while the raw material process is the largest contributor to land occupation, it is only the fourth largest contributor to total biodiversity impact. Additionally, although finishing is the smallest contributor to land occupation, spinning is the smallest contributor to biodiversity impact. These changes indicate that the process locations, as contained in the characterization factor, influence polyester’s biodiversity impact. Unlike the other textiles for which raw material land occupation is so large, and thus dominant in the biodiversity impact results, polyester’s land occupation is relatively small, so the characterization factor exerts an influence on biodiversity impact.

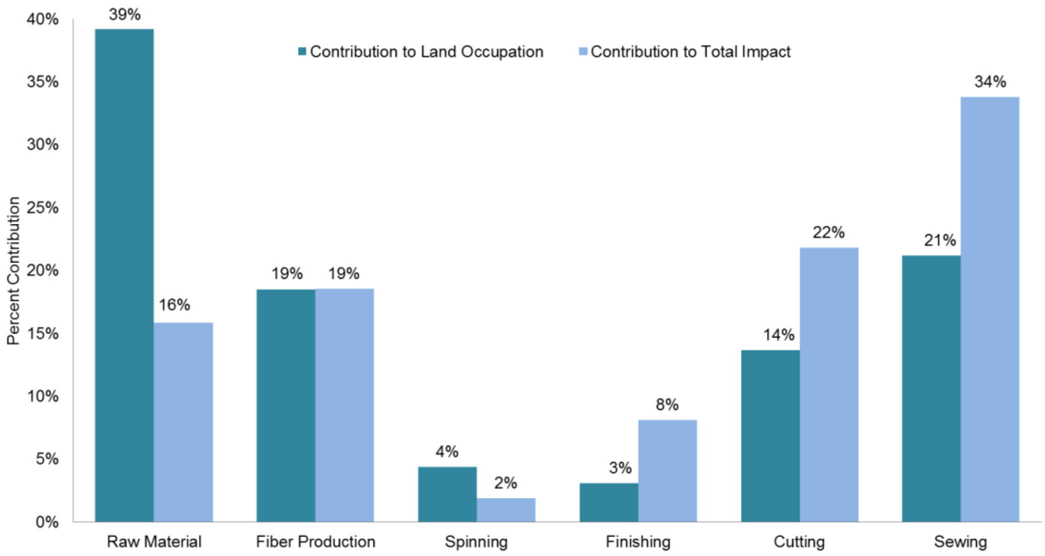


Figure 11. Percent contribution of land occupation and biodiversity impact of each unit process to the total biodiversity impact (potentially lost non-endemic species per functional unit) and land occupation (m2*years)

5.4 Contribution of Electricity Impacts

As reported in Table 8 in Section 4.5, electricity contributes less than 1% to the total combined foreground plus background biodiversity impacts of cotton, wool, and lyocell, yet in polyester it accounts for nearly 75%. Although the land occupation required for polyester electricity production and resulting biodiversity impact are an order of magnitude larger than the other materials, the relatively high contribution of electricity is due to the fact that polyester's foreground biodiversity impact is orders of magnitude smaller than the other textiles' impacts.

As mentioned previously, biodiversity impacts of land occupation for electricity production are included in this case study as an example of how the model can be used to evaluate and incorporate background processes. We find that a lack of primary data on electricity consumption per unit process and location of occupation for electricity generation, as well as the fact that Ecoinvent provides only country-wide electricity production mix data, reduces the accuracy and meaningfulness of these results. These data gaps mean that the same world average median urban characterization factor was used to calculate the results for all unit processes for all four textiles; and that production mixes for the U.S., China, and Europe were broadly used to calculate land occupation requirements for each unit process. This additionally means that energy consumption per functional unit, which was drawn from literature, was the primary variable differentiating our results. In practice, companies are likely to be able to gain access to energy consumption data, but may have a more difficult time identifying the location where electricity is generated, and will likely need to rely on countrywide Ecoinvent land occupation data. For the calculated biodiversity impact of electricity generation to be more accurate and meaningful, electricity consumption data should be gathered directly from the supplier and a general location of electricity generation is needed; increased availability of regionally specific data in Ecoinvent would also be useful.

6 Limitations & Conclusions

The primary objective of our study was to explore the robustness of an emerging model for incorporating land use impacts on biodiversity into LCA. Through our results and analysis we identify four key limitations to using the model as it exists, which prevent it from being ready to incorporate operationally alongside other environmental indicators in LCA. Although with refinement and increased data availability, the model has potential for future use, it is currently better suited for providing broad generalizations about land occupation impacts on biodiversity than for specific use in decision making or for conducting refined product system assessments.

6.1 Limitation 1: High characterization factor uncertainty

The first limitation of using the model is the high level of uncertainty in the resulting characterization factors. As explained by de Baan et al. (2013b) in their report, the sensitivity parameter, or relative decrease in species richness, used to calculate the characterization factors contributed between 67% and 96% of the variance. This uncertainty is due to a lack of taxa- and ecoregion-specific data, which required that some values be aggregated across larger spatial units than ecoregions, such as biomes or the globe (de Baan et al. 2013b). Taking uncertainty into account, all of our unit process biodiversity impact values range from the land occupation having a detrimental effect (a positive biodiversity impact) to a beneficial effect on biodiversity (a negative biodiversity impact), as does each total product system (shown in Figure 12).

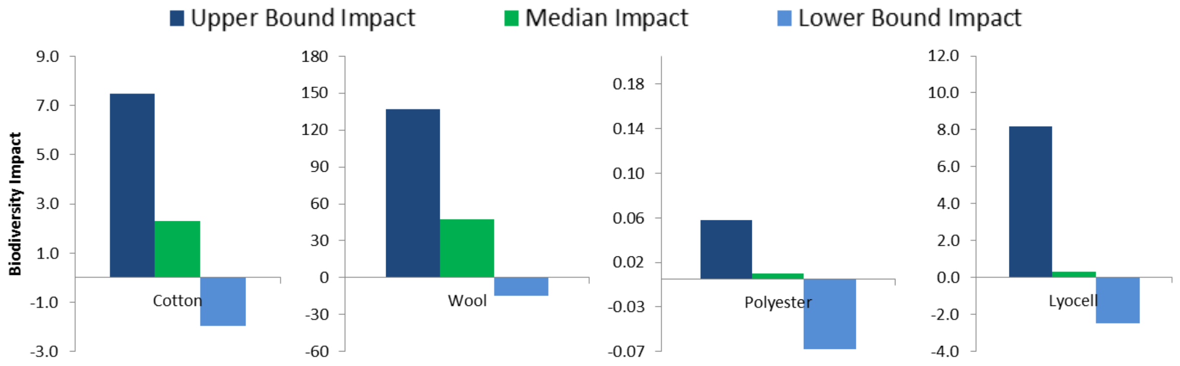


Figure 12. Range of total biodiversity impact per textile as calculated using the high (dark blue), median (green) and low (light blue) characterization factors of a 95% confidence interval. Biodiversity impact is shown in thousandths of a potentially lost non-endemic species per functional unit

For cotton, wool, and lyocell the majority of this range falls within the positive domain, indicating a detriment to biodiversity; for polyester the majority actually falls in the negative domain, indicating a biodiversity benefit. This uncertainty limits the confidence with which conclusions can be drawn from these results, and with which our findings could be used for decision-making. In effect we find that wool t-shirt production might lead to the greatest biodiversity loss, or it might produce the greatest gain. Still, under both high and low uncertainty scenarios, raw material unit processes remain the greatest contributors to total impact for cotton, wool, and lyocell; wool continues to have the greatest impact, whether beneficial or detrimental, of the four textiles.

6.2 Limitation 2: Cannot capture nuances in land use types

The second significant limitation is that the characterization factors consider only four broad land use types, even though land is used in myriad ways. This broad classification scheme means that the model cannot distinguish between finer land cover types such as crop type, vineyard, or orchard within agriculture, or high and low intensity industrial or residential land uses within the urban classification. Similarly, land use management strategies, such as organic and conventional farming or sustainable versus traditional grazing cannot be differentiated. In addition to the wool example provided in Section 6.1, the cotton used in the assessed t-shirt is made from 100% organic cotton. The extensive nature (i.e. lower yield, higher land occupation) of organic farming is often cited as being less ecologically damaging compared to more intensive conventional farming practices, because the management technique allows the physical and biological processes of the land to continue functioning. Yet this potential benefit cannot be captured using the characterization factors applied in this study; a high-yield cotton farm will always show a lower impact result as compared to a low-yield cotton farm in the same ecoregion. For a company like Patagonia seeking the most sustainable options, and committed to sourcing 100% organic cotton, it is important to be able to distinguish between land use management techniques when making sourcing decisions.

Consensus is also lacking among the multitude of existing global land use and land cover maps (de Baan et al. 2013b). Harmonizing and updating global land cover maps to include management regimes and fine land use types is an enormous effort, but one that may be necessary for these characterization factors to be used effectively. Refinement of the characterization factors to align with these narrower land classifications will increase the resolution of the information provided by such impact assessments. Although some research proposes a classification scheme using more than 75 land use types (Koellner et al. 2013a), it is more difficult to generate a refined database of characterization factors for such detailed land classifications, representing a significant trade-off if used in the currently available characterization factor model.

6.3 Limitation 3: Need for location-specific data

Third, to use this database of characterization factors meaningfully requires knowledge of the locations where facilities or processes occur. For many companies, particularly those lacking transparency in their supply chain, heavily reliant on commodity products, or sourcing materials from a multitude of locations, this information may be difficult or impossible to obtain, and regional accuracy will not be possible in the results. Although a world average characterization factor can be used to supplement this data, this adds a further layer of uncertainty to the results.

6.4 Limitation 4: Captures limited aspects of biodiversity

Finally, to reiterate Section 2.3 of this report, biodiversity is complex and this model captures only limited aspects of it. The calculation of biodiversity loss or extinction potential in this model is based on the species area relationship (SAR) model, as well as the sensitivity of species to land use change, which is based on species richness. These two measures of biodiversity loss do not capture the many other aspects of biodiversity, which are considered to be equally important for healthy environmental conditions. Genetic diversity, or the diversity within a species is critical to the long-term survival of a species, but this aspect is currently not captured. Ecosystem diversity is also not incorporated and therefore leaves out the consideration of many different types of habitat, which can support a distinct variety of species. The relative abundance of species is also not captured and each species is weighted equally, therefore species with a higher ecological value are considered equal to all others. These measures of biodiversity loss also ignore the inherent functions of biodiversity, functions that include nutrient cycling, gene flow, and other ecological and evolutionary processes. Biodiversity is difficult to measure quantitatively, and has thus far proved difficult to incorporate operationally into LCA, particularly due to lack of data and the complexities of modeling biodiversity. Even with developments and improvements, one model cannot capture the depth and complexity of biodiversity necessary for its proper measurement.

6.4.1 Relationship to Conservation Objectives

De Baan et al. (2013b) note that areas with high land occupation and transformation characterization factors in their study overlap with the biodiversity hotspots identified by Myers et al. (2000), displayed in the maps in Figure 13.

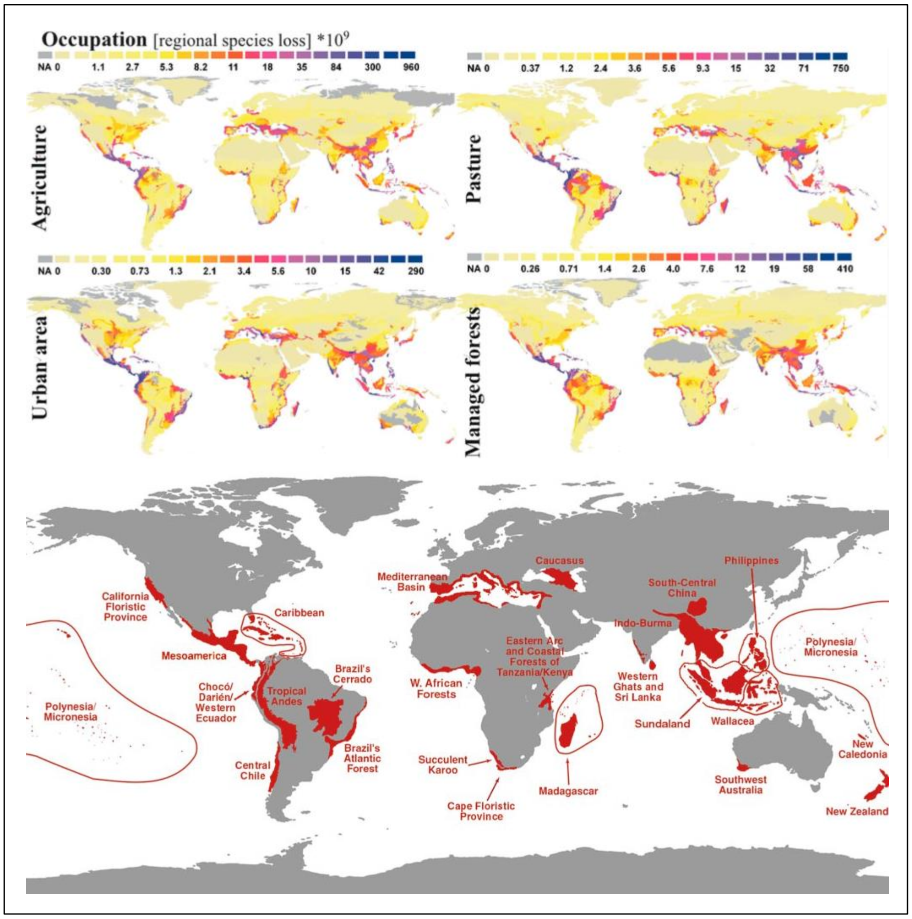


Figure 13. Map of median occupation characterization factors based on plants from de Baan et al. (2013b) (top) to compare with Myers et al. (2000) Biodiversity Hotspots (bottom) with hotspots in red

Biodiversity hotspots are defined as areas that have both high concentrations of endemic species, and that are experiencing an unusually high rate of habitat depletion (Myers 1998).
The darker areas of the de Baan et al. (2013b) map (top) correspond with biodiversity hotspots shown in red on the Myers et al. (2000) map (bottom). Although biodiversity hotspots have been suggested by some as a means to set conservation priorities, and biodiversity hotspots may be an important indicator of previous land use conversion, they may not always meet desired conservation goals as resources are inevitably too scant for protecting all threatened and endangered species. Brooks et al. (2006) identify biodiversity hotspots as a reactive global conservation priority, distinct from proactive priorities in that the focus is on areas of high vulnerability (such as those with which high characterization factors are associated) rather than areas of low vulnerability (such as those with which low characterization factors are associated). Large, undisturbed areas are considered low-vulnerability; yet provide great potential for conservation. Depending on whether the objective of the user is to conserve prime biodiversity habitat for the future or to conserve already heavily degraded land, the conservation strategy will change. De Baan et al. (2013b) recognize that their characterization factors are intended to assess impacts reactively, or retrospectively, as they look specifically at historical, average land use changes. Thus de Baan et al. used land use scenarios for 2050 to calculate prospective characterization factors, though this was done for only 19 ecoregions of the Amazon. They found that characterization factors changed most notably in ecoregions with large projected deforestation rates (de Baan et al. 2013b). As developments in the data and methods progress, the prospective approach suggested and briefly tested by de Baan et al. (2013b) for calculating the potential future loss of species through marginal land use changes may be more applicable in situations where there is a large portion of undisturbed land that faces serious future land use threats (de Baan et al. 2013b). The important point to be drawn is that propagating one set of characterization factors, such as those developed by de Baan et al., throughout an industry or LCA implicitly assigns value to certain facets of biodiversity and conservation priorities, while neglecting others which may be equally important and relevant.

6.5 Limitations of the Case Study

In addition to the limitations of the characterization factor, which are inherently carried into our case study, a limitation of our case study is that we did not model transformation or permanent impacts. In order to measure total global biodiversity impacts, occupation, transformation, and permanent impacts must all be summed. This is necessary since occupation and transformation impacts assess reversible regional extinctions whereas permanent impacts measure irreversible, permanent extinctions based on endemic species. Thus, the results of our study indicate only reversible extinction risk rather than permanent extinction of endemic species.

7 Recommendations

7.1 Recommendations for the Model

De Baan et al. (2013b) recognize that a number of factors limit the applicability of their regional characterization factors, and accordingly outline recommendations for improvements and future research. Generally increasing the quantity, diversity, and resolution of data on species and land use will lead to improved characterization factors, including those reviewed in this study for land occupation. In particular, de Baan et al. recommend:

1. Adding new species data to the WWF database from which biodiversity and global land use data are drawn. This will produce more accurate characterization factors. In particular, increasing data on taxonomic groups currently underrepresented in research, such as reptiles and amphibians, would be useful in improving the characterization factors.
2. "Better data on taxa- and eco-region specific habitat suitability for different land use types (de Baan et al. 2013b)" will improve the certainty of the model by reducing the need to aggregate input parameters across broader spatial units than ecoregions. Increasing the detail, accuracy, and agreement between global land use classification maps could also reduce uncertainty.

Although any improvement in data robustness will subsequently improve the applicability of this model, it will still be limited by the high uncertainty that arises from the intricate nature of biodiversity, particularly as it relates to fitting within an LCA framework. Measuring only one aspect of biodiversity, such as species richness, leaves out the many other aspects that could be considered such as genetic diversity, functional diversity, structural diversity, and spatial distribution. Therefore, even with increased data on species richness at a high-resolution spatial scale, many aspects of biodiversity would be omitted, which limit the potential for this model as tool to be used on its own. With regards to application within the apparel industry, and perhaps in corporate sustainability decision-making generally, our greatest recommendation for the development of future models is to prioritize the incorporation of a highly defined land use classification scheme. Although data availability is currently an obstacle, when it comes to product sourcing, company’s need to be able to identify the benefits of one land use management strategy over another, in addition to differences arising from land occupation and location. When deciding to source 100% organic cotton, for example, a company should be able to quantify the impacts of that decision on biodiversity alongside its affect on water consumption, environmental toxicity, and global warming.

7.2 Recommendations for Patagonia

Although the limitations of the model prevent us from recommending that it be used operationally alongside other LCA indicators, the model as applied through this study reveals important information regarding land use impacts on biodiversity. A review of the results does provide interesting insight into Patagonia’s product systems and the complexities of trying to quantify biodiversity, which can help guide future sourcing decisions, even though we cannot recommend relying firmly on the numbers provided by this model. Our analysis leads us to the following recommendations for Patagonia and other companies looking to evaluate their biodiversity impact from land use.

Agricultural and pastoral land uses contribute significantly to the overall biodiversity impact of a t-shirt due to their large land requirements per output, signifying that Patagonia, as well as other apparel companies using agriculture or grazing, may not need to look beyond total land occupation to approximate their biodiversity impacts. Relying on the results of this model would indicate that increasing yields from these processes is one way to reduce the per-unit biodiversity impact of a product system. However, increasing yields is typically tied to more intensive land use, which may put greater pressure on a particular ecosystem, and require inputs of fertilizer, pesticides, and water, among others. Moving to a higher-yield management strategy (e.g. conventional cotton farming from organic) may simply shift land occupation impacts to other environmental categories. For example, the burden of impacts could shift to water pollution, or affect different aspects of biodiversity such as microbial diversity, in turn degrading soil fertility. As an alternative, we recommend that Patagonia look qualitatively at the land use of its supply chain, with a particular focus on identifying methods for improving agricultural and pastoral processes. As a part of this qualitative assessment, it would be beneficial to fully understand the land management strategies used by suppliers, and to research the benefits or negative impacts of particular land management practices such as organic farming and holistic land management on biodiversity to inform sourcing decisions. To decrease impacts associated with processes producing the raw materials, such as cotton, wool, and timber, Patagonia should continue to develop partnerships with organizations like The Nature Conservancy and suppliers like Ovis XXI. Working with these groups, Patagonia can support the use of innovative sustainable land management strategies. Patagonia can also continue to work closely with their suppliers to minimize inputs that may have harmful effects on biodiversity, whether in their production or use phase. While these impacts on biodiversity may not result from land use directly, they may be the result of the other harmful inputs to the environment. Decreasing water use, chemical use, water pollution, and fertilizer may all help to minimize impacts on biodiversity. Patagonia has little capability to decrease the land use associated with urban processes such as sewing, spinning, or knitting. Instead, Patagonia could look into conservation and biodiversity offset options to lessen the impacts resulting from their urban land uses, such as forest restoration, natural habitat preservation, or habitat remediation.

Although this model does not yet provide the granularity necessary for us to recommend its use widely within apparel life cycle assessments, primarily due to its inability to distinguish between specific land use types, Patagonia and the Sustainable Apparel Coalition should continue their pursuit of a methodology for quantifying biodiversity impacts. Biodiversity is critical for a healthy future, and we cannot afford to neglect it in corporate decision-making. Pressure and support from the apparel industry and others will help to drive the research necessary to develop a robust model that allows companies to minimize impacts from land use on biodiversity.

Appendix I

Calculating the Characterization Factors

Due to the dependence of our project on the regional occupation characterization factors developed by de Baan et al. (2018b), we have included a summary of how they were calculated.

Equation 1 is describes the species-area relationship (SAR) used in ecology, which was modified as shown in Equation 2 to correct for the overestimation of species loss associated with the SAR. Equation 2 is the matrix calibrated species area relationship model, which allows for species to exist on human modified land (the so-called "matrix").

$$S = cA^z \qquad \text{Eq. 1}$$

$$\frac{S_{new}}{S_{org}} = \left(\frac{A_{new}}{A_{org}}\right)^z \qquad \text{Eq. 2}$$

The z-value, a constant in the matrix SAR is adapted to *z'*. *z'* (Equation 3) represents the ***suitability*** of the matrix. It is dependent on the species' sensitivity (σ) to varying land use types (i), as well as the composition or relative frequency of land use types (p_i) in the human-modified matrix. The adapted z-value lowers the curve in the species–area relationship thereby predicting lower species extinction risks from habitat conversion.

$$z' = z \sum_i^n p_i \sigma_i \qquad \text{Eq. 3}$$

Species sensitivity (σ) to various land use types is given by the relative difference in the number of species (species richness) between a natural reference habitat and the species richness of a land use type (Equation 4). Previous studies by de Baan et al. (2013a) derived local characterization factors using this calculation.

$$\sigma_i = CF_{loc,i} = \left(\frac{S_{ref} - S_i}{S_{ref}}\right) \qquad \text{Eq. 4}$$

The species lost variable is calculated by subtracting the species richness in the "new" human modified matrix ($S_{new,g}$) from the species richness in the "old" reference habitat ($S_{org,g}$). Equation 5 calculates the total number of non-endemic species lost in each eco-region and in each taxonomic group (g) due to the cumulative land use in each eco-region.

$$S_{lost,g} = S_{org,g} - S_{new,g} = S_{org,g} - S_{org,g} * \left(\frac{A_{new}}{A_{org}}\right)^{z'} \quad \text{Eq. 5}$$

The total non-endemic species lost in an ecoregion are then allocated to the differing land use types, relative to their frequency. An allocation factor is calculated for each land use type *i* and ecoregion *j* per Equation 6.

$$a_{i,j} = \frac{p_{i,j} CF_{loc,i,j}}{\sum_i^n p_{i,j}\, CF_{loc,i,j}} \quad \text{Eq. 6}$$

Characterization factors for occupation are calculated by combining the non-endemic species lost per ecoregion and taxa variable, the allocation factor. Multiplying these factors results in non-endemic species lost for specific land use types in each ecoregion based on the relative frequency of a land use in the ecoregion. The species lost factors account for species' differing sensitivities to land use activities. The product of species lost and the allocation factor are divided by the area occupied by a particular and use type *i* in a particular ecoregion *j*.

Characterization factors for occupation for each land use type and eco-region

$$CF_{Occ,reg,i,j,g} = \frac{S_{lost,nonedem,j,g} * a_{i,j}}{A_{i,j}} \quad \text{Eq. 7}$$

Appendix II

Supplier Questionnaire for Primary Data Collection

A similar questionnaire to the one provided here, adapted for the textile and unit process, was sent to each supplier. A table was provided for suppliers to record their responses.

Please answer these questions to the best of your ability in the table provided on the page 2.

- Please select several farms, which are representative of the farms that supply cotton to the Texas Organic Cotton Marketing Cooperative.
- If possible, please also provide a list of all farms, which produce cotton for the Texas Organic Cotton Marketing Cooperative, including their locations and sizes, if possible. This can be entered into the provided excel spreadsheet (email attachment). This information can also be provided whatever way is most convenient for your party.

1. A. How **many** farms produce organic cotton for the TOCMC?

   B. Identify the cotton farming operations by ***name*** or any other identification that are used to produce cotton and are ***most representative*** of all the cotton supply farms in terms of size and location?
    1. What is the **size** of this property in hectares? *If other units are used, please specify.*
    2. How **many hectares** are used for cotton production on this property?
    3. What is the **total amount** (weight) of cotton that is produced on this farm annually?
    4. What is the **total amount** (select unit) of cottonseed that is generated from this farm annually?
    5. How **much** cotton (weight) is acquired from this farm for Texas co-op annually?
    6. Other than cottonseed, are there any other **co-products** of cotton production?

   C. What is the ***location*** of these farming operations (address or coordinates)?

2. How long has this farm been on this land?
   A. What ***length of time*** (years/months) has this cotton farming operation occupied this tract of land?

   B. Has the **amount** (hectares) of land used by this cotton farm increased over the past 20 years? ***Yes or No***

   If **YES**, what year did the size change to the current size (hectares)?

3. How is the **land used** at this cotton farming operation? Select a land use type from the list provided at the end of the document.

4. Before this operation owned and operated this land, how was this **land used**? For historical land use classification use the list provided at the end of the document.

Appendix III

Modeling Species Extinction: SAR vs. EAR

There are three popular models upon which species extinction estimates are based: the Species-Area Relationship (SAR), the matrix-calibrated Species-Area Relationship, and the Endemics-Area Relationship (EAR). Both the matrix modification of the SAR and the use of the EAR aim to compensate for the overestimations of species extinction rates yielded from tracing backwards along the traditional species-area curve of the SAR model (see backwards SAR in Figure 14).

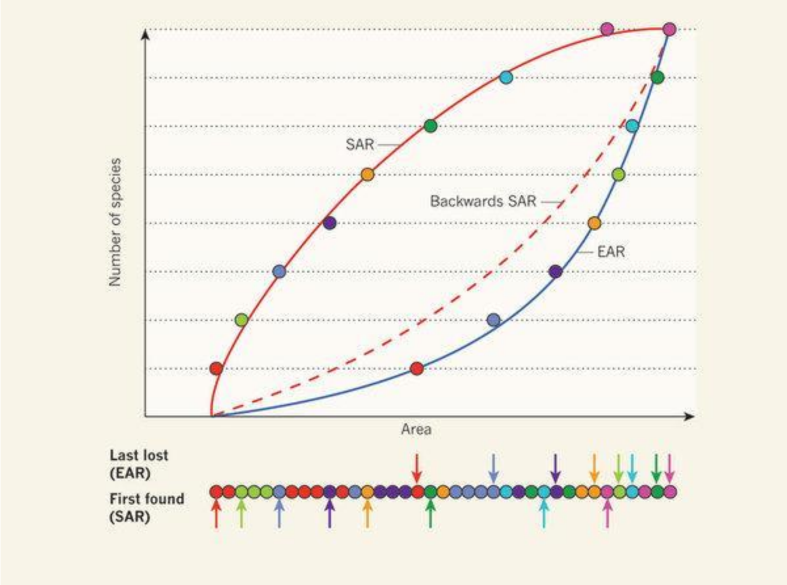


Figure 14. Estimating species extinctions due to habitat loss, from Rahbek, C. and R. K. Colwell (2011)

The traditional SAR model is based on island biogeography theory developed by MacArthur and Wilson in the 1960s, and concludes that larger islands (habitat surrounded by unsuitable habitat) contain more species than smaller islands. This model proposes that the number of species on an island is a function of the immigration and extinction rates, relying on the assumption that the population size of each species is proportional to the size of the island or fragment (MacArthur and Wilson 1967). This species richness can be described by the power relationship $S = cA^z$, in which S is the number of species in a habitat type of area A, and c and z are constants. This relationship estimates the area required to sample the first individual of a species. In order to calculate expected species lost, one can simply extrapolate backward along the species-area curve.

The shortcomings of the SAR model that sparked introduction of the matrix-modified SAR model include the assumption that: 1) land use between habitat areas being modeled, otherwise known as the matrix, is inhospitable for species persistence, and 2) there are no negative impacts of the matrix on habitat fragments. Since in reality, some species are able to persist on human-modified land, a refinement of the SAR extinction approach was made by adding terms to the power relationship that account for taxon-specific responses to individual components of the matrix and edge effects (Koh & Ghazoul 2010; Koh et al. 2010). This matrix-calibrated species area relationship curve effectively lowers the curve of the SAR (de Baan et al. 2013b)

Despite improvements in the SAR approach made through the matrix-calibration, some criticisms persist over estimating species loss based on either SAR or matrix-calibrated SAR. For instance, if species of individuals are clumped, as is often the case in nature, then the area added in order to find the first individual of a species is much smaller than the area that must be removed to eliminate the last individual of the species. This species distribution factor is the driver leading to overestimated extinction rate estimates. In other words, it takes a greater loss of area to cause extinction of a species than it takes to find one, and this bias holds for any power law species area function (SAR or matrix-calibrated). He and Hubbel (2011) estimate that using the SAR potentially overestimates extinction rates by over 160%, depending on the taxon and region.

Proposed by Harte and Kinzig (2000), the EAR is nearly opposite from the SAR, allowing for the estimation of extinction based on the loss of habitat area by measuring the area required to sample the last individual of a species, as opposed to the first. He and Hubbell (2011) found both mathematically, and in examples using realistic spatial patterns of trees and birds, that the backwards SAR curve always lies above the EAR curve (Figure 14), thus overestimating expected extinction rates (Carsten & Colwell 2011).

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