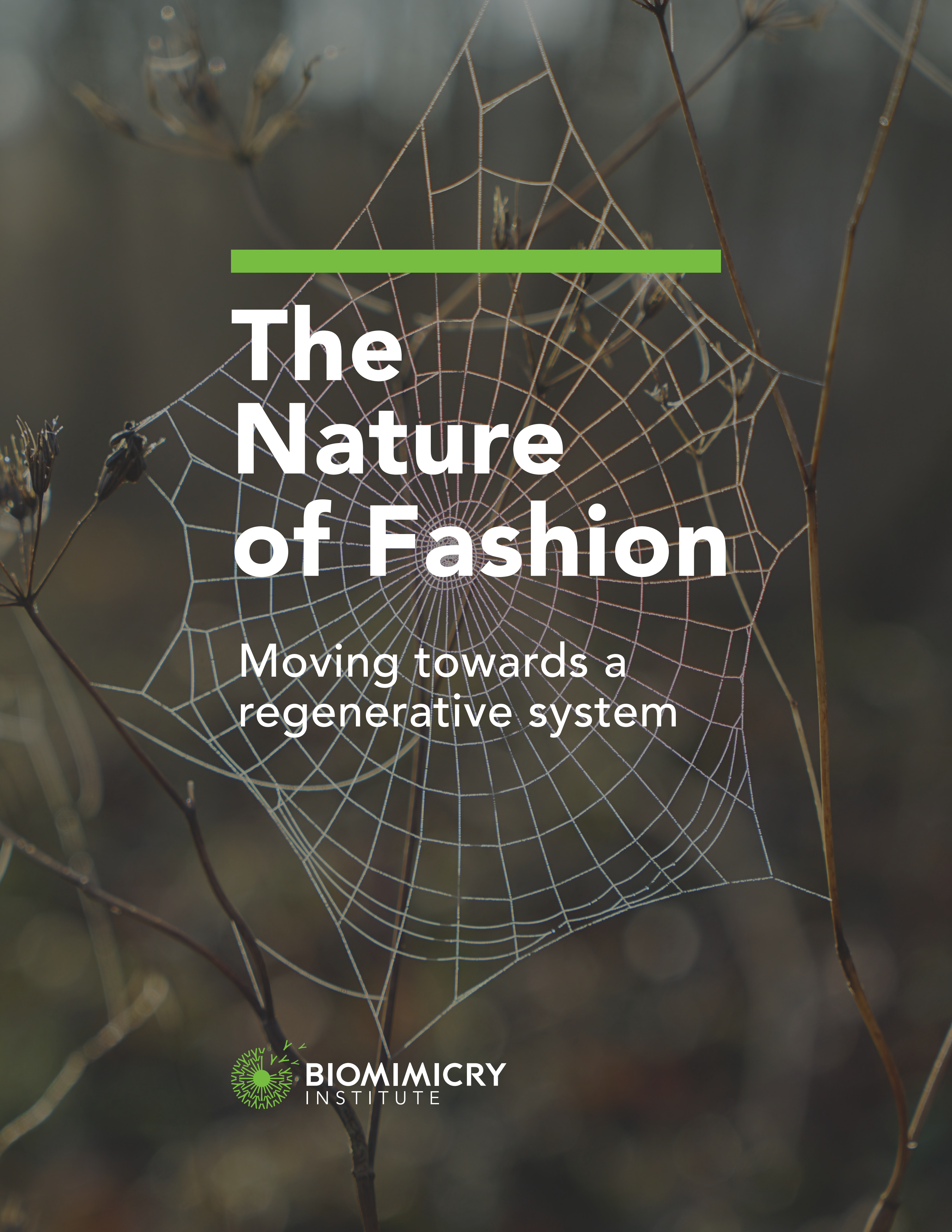


The Nature of Fashion

Moving towards a regenerative system

BIOMIMICRY INSTITUTE

Contents

This report was conceived in a different world. It was a world where consumption was continuing faster than ever before, driven by the availability of cheap petroleum. It was a world of fast fashion, where the price of apparel had ignored inflation and remained unchanged for 30 years,[1] and where fashion waste was dumped by the truckload every second.[2] It was a world that most of us knew must cease, yet almost all of us continued to participate in. Due to COVID-19, with its social and economic fallout, a different reality has emerged.

All the old rules have been put on hold, making now the perfect time to write the new ones.

Foreword

We live in a biosphere, a physical network of living beings that spans the entire globe.[3] Within this web, materials are constantly being dispersed. Some organisms use energy from the sun to concentrate life's building blocks, only for them eventually to become dispersed once again.[4] The process is driven by the fundamental laws of physics. In fact, without this cadence, there would be no life.[5,6,7] The circular economy seeks to replicate nature's cycling, and one of its premises is that infinitely reusing our industrial materials can make commerce compatible with nature.[8] But everything we do, all of our industry and economic activity, still exists within the natural system. The same laws of physics that drive natural material cycles make it impossible to isolate the technical ones.[9,10,11] **Our man-made material loops always, inevitably, leak.**

It's safe to say that no one ever looked at a barrel of oil and thought, "That would make a nice-looking dress." And yet, for nearly 80 years, we have collectively looked past the ill-effects of petroleum and focused solely on the versatile, low price-point clothing that polyester makes possible. Recent years have seen growing interest from the fashion industry to move towards a circular economy, an economy that is regenerative by design. Biomimicry, the practice of emulating nature's strategies and processes in human design, is one of the schools of thought that originally inspired the development of the concept of a circular economy, an economy that ideally would function as a natural system. What a circular economy looks like and the ideas on how to get there are continually evolving, informed by experts all over the world. **As the Biomimicry Institute, we hope to add to the evolution by answering the question: What would the fashion industry look like if it acted like a natural ecosystem?** This report shows what we learned and makes some observations that should inform the development of new business models—and the sunsetting of others—for a circular fashion industry.

As we spoke with industry experts and reviewed the mass of recent research and conclusions articulating how to make fashion responsible, sustainable, regenerative, and circular (Appendix A), we realized that many of the suggested circular economy solutions do not align, and cannot align, with biological principles and the laws of physics. Those insights informed this report. It deals only with system boundaries and explains how energy and materials cycle at the highest level—the biosphere—and how fashion might embrace its existing reliance on natural ecosystems to more deeply emulate those cycles. With that understanding, we hope to continue this research in the future and expand on how biomimicry at the systems level can further inform the evolution of a circular fashion economy.

By realigning ourselves with what occurs in nature, we can design a next-generation textile production model that recognizes its connections to the biosphere. In section one of this report, we explore the material flows that underpin natural systems and show that the first thing we must learn from nature is how to design for decomposition and dispersal. We identify some important elements of ecosystem functioning, compare them to the flawed industrial system we have today, and explain why we should think of fashion systems as inside natural ones (rather than as having separate biological and technical loops). In section two, we show how the fashion industry, relying on advances in regenerative agriculture, cellulosic fibers, fermentation, and gasification can work with existing technology and nature to jump-start the transition right now. In section three, we propose a set of specific recommendations designed to give philanthropists and investors guidance on the next steps to take.

We believe an industry based on these guidelines can enhance ecosystems to boost biodiversity, build soil, support communities, and clean up existing pollution.

"We have not been successful at recycling. After 40 years of trying, we have not been able to make it work."[12]

Dame Ellen MacArthur,
Founder and Chair of Trustees,
Ellen MacArthur Foundation

SECTION 1

Catch and Release

Sometimes it helps to take a broad view to address a narrow problem, like what we humans should wear.

Natural materials cycle endlessly. This constant flow of materials underpins all life on Earth. But cycles in nature are vast and open, and compounds like DDT (banned 20 years ago) and the toxic PFASs used to make our clothing stain-repellent continue to find their way into the tissues of polar bears thousands of miles from their point of manufacture.[13,14,15] Nature cannot distinguish between good molecules and bad, nor can their movement be stopped. The essence of the second law of thermodynamics is that disorder increases over time. This means nature disperses.[16] * Dispersal is embraced in nature by utilizing universal building blocks, particularly carbon. Trees and berry bushes, the herbivores that consume them, and decomposers like bacteria and fungi all run on the same basic framework of fats, sugars, starches, and proteins. When a bird eats a berry and poops, or dies, those remains decompose and return to the soil as nutrition for the next tree, which combines these nutrients with energy from the sun and carbon dioxide from the air to start the cycle again. We have all observed this, but its elegance is difficult to emulate.

Aiding this process, nature works with a global net to catch such valuable building blocks and prevent them from being lost, or aggregating in the wrong place. Ocean currents and fungal mycelium networks in the soil collect discarded carbon and nutrients and cycle them back to a "user" who finds them valuable in sustaining life.[17,18] In addition to this global net, natural cycles rely on three main types of organisms—primary producers, consumers, and decomposers—to function in a dynamic state of finding balance, or equilibrium. These three types of organisms reflect how carbon moves from one species to another, and between organisms and the environment. "Photosynthetic organisms convert the energy of the sun to chemical energy in carbon molecules, and consumers gain energy by eating those molecules. Thus, the carbon cycle also traces the transfer of energy through ecosystems."[19]

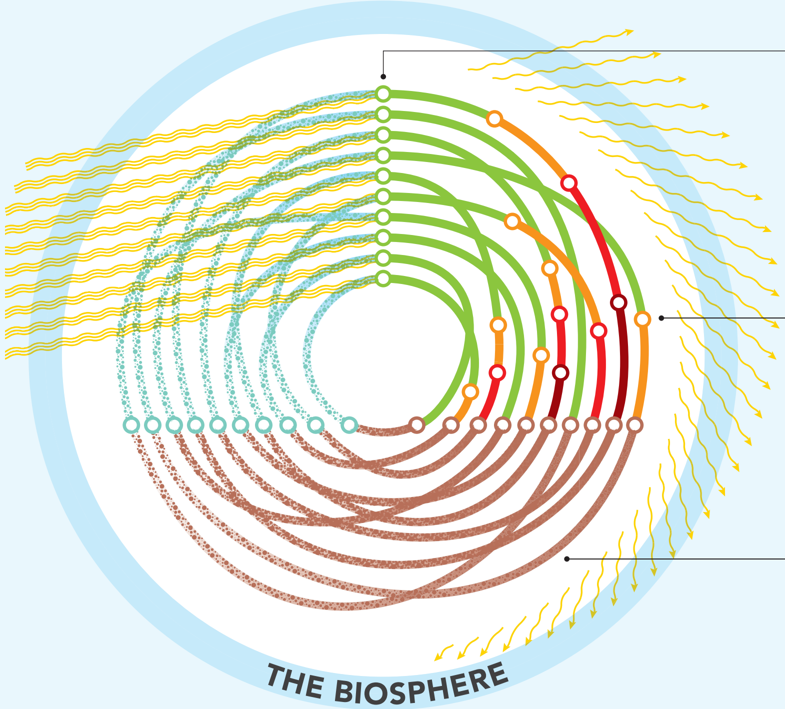
These are the elements of the natural cycle and, by extension, all natural ecosystems. It is a "catch and release" system powered by the sun that has worked for billions of years. There is no human approximation of this effort that comes close to working as well.

The goal of this section is to more deeply understand how matter and energy are inextricably linked and highlight the valuable roles of the three stars of our biological show—producers, consumers, and decomposers. In doing so, we build upon the work of Cradle to Cradle, the Circular Economy, Doughnut Economics, and the many luminaries who apply nature's laws as the guard rails of human industry.

** We recognize there is disagreement around the applicability of the second law of thermodynamics to macroscale materials. We have written this report from the perspective that thermodynamic and informational entropy are two aspects of the same underlying physical law and that all increases in disorder are explicable using some combination of the two.*

Figure 1.
Nature's Dynamic Equilibrium

Represented as a diagram, flows of energy and matter in nature look more like a whirlpool than a simple loop. Nature achieves dynamic equilibrium through an open, dissipative system. Equilibrium is maintained because the materials in the system are benign and cycle continuously, and because the whole is powered by constant in-flows of free energy from the sun.



Natural cycles have three main parts:

Primary Producers
Photosynthetic plants and algae combine free **solar energy** with disordered **material building blocks** from soil, air and water to create highly ordered, energy-dense structures.

Consumers
Includes all **herbivores** and **carnivores**, which break down energy-dense structures and use the stored energy and materials to construct their own tissues, creating physical waste and dissipating energy.

Decomposers
Bacteria and fungi break down material to basic building blocks, using up remaining energy and making the physical building blocks available for use by primary producers.

THE EXISTING FASHION CYCLE

Humans are mimics. It's part of our success, and we have designed industrial systems that attempt to imitate the way that nature cycles materials. Yet there is a gulf between the best of human endeavor and what nature achieves. Recycling has grown into a $200 billion industry,[20] but that is miniscule compared to the total global consumption economy, which was worth an estimated $86.6 trillion in 2019.[21] There are also increasingly serious structural challenges threatening the growth of the recycling industry. For example, China recently implemented its National Sword policy, effectively reducing recycled waste imports from G7 countries by 50%.[22] The ban also applied to textile waste.[23] "Now all this trash is building up in Japan [and elsewhere] and there's nothing to do with it; the incinerators are working at full capacity," says Eric Kawabata, the Asia-Pacific general manager for TerraCycle.[24]

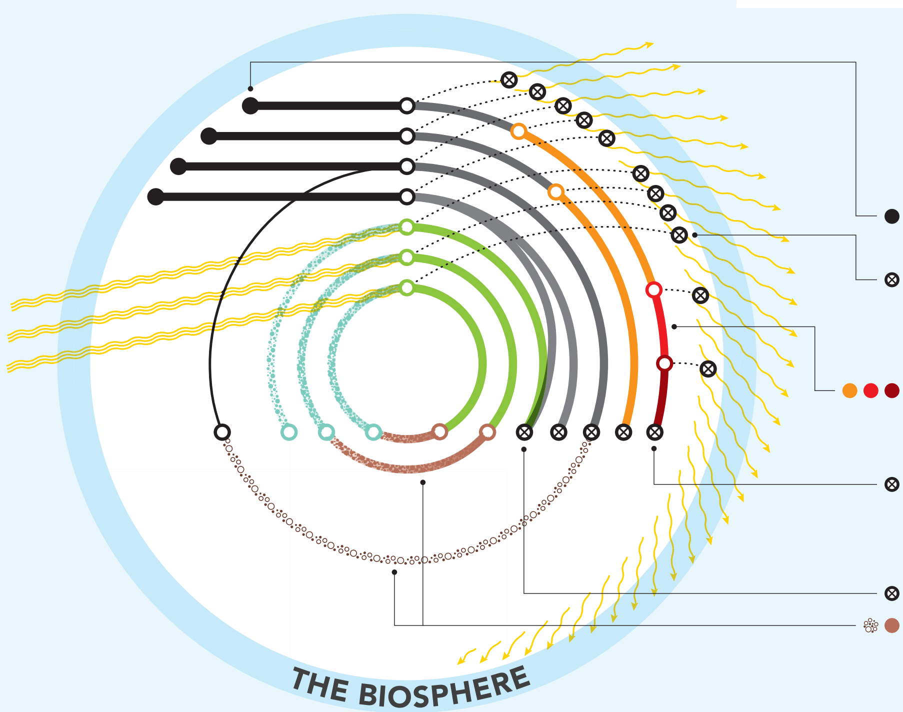
In the fashion industry, the production of virgin yarn and fabric is equivalent to primary production in the biological cycle. Yet, in place of plants and algae using photosynthesis to assemble basic building blocks, the fashion industry mostly relies on fossil fuels. At at least 60% of textiles are currently made using fossil fuel-based synthetic fibers.[25] Unlike nature's material palette, synthetics do not contribute beneficially to the biosphere after their short-term human use. As a result, synthetic materials quickly exceed the carrying capacity of the biosphere wherever they end up. Current strategies for encouraging a more circular economy fail to address this challenge. Synthetics, however, lack a desirable contributory function beyond human's short-term use. Like life, polyester is carbon-based and subject to entropy, but dissipated polyester is a hazard that is costly to collect and does not decompose naturally back to building blocks of use in primary production. Instead, polyester and other plastics undergo weathering and are broken down by UV light into useless and toxic microfibers, which then accumulate in the environment.[26]

The link between decomposition and primary production is broken, meaning that nutrients that in a natural system would be "food" for primary production instead become pollution.[27] As a result, synthetic materials quickly exceed the carrying capacity of the biosphere wherever they end up. Current strategies for encouraging a more circular economy fail to address this challenge. At the moment, the circular economy is also "optimised to grow the circulation of materials, irrespective of whether this goal supports total systems improvement and the ecological reality of genuine biophysical limits," say professors Kate Fletcher and Mathilda Tham in the Earth Logic Fashion Action Research Plan.[28] If the fashion industry does not recognize the carrying capacity of the earth, there is great risk that the benefits of material reuse will be offset by increasing consumption.[29]

Figure 2.

Current Fashion System

Unlike the natural system, the paths traced by fossil fuels-based energy and materials start and stop in the biosphere, with very few closed loops. What exists is restricted to its own channels, with almost no universality and crossover except from the escape of toxic pollutants.



Fashion industry material flows lack equilibrium in several important ways:

Raw Materials
60% of textile fibers are synthetics derived from **petrochemicals**. Processing is powered primarily by fossil fuels that release greenhouse gas pollution.

Consumption
Includes the first use of clothing plus **reuse, remanufacturing, and recycling**. Synthetic fibers (virgin and recycled) become waste, which accumulates in soil, air, and water as **pollution**.

Waste and Recovery
Decomposers are mostly absent in this system. **Blended fibers** prevent recovery. **Composting** and **thermal energy recovery** are rare exceptions that return materials to basic building blocks.

In 2017, Textile Exchange asked over 50 textile, apparel, and retail companies (including Adidas, H&M, Gap, and Ikea) to increase their use of recycled polyester by 25% by 2020. The companies exceeded their commitment by moving to 36% recycled content two years ahead of schedule. With even more companies signing on to the challenge, Textile Exchange expects one-fifth of all polyester will be recycled by 2030.[30] Problem solved? Not exactly.

THE PROBLEM WITH PLASTICS

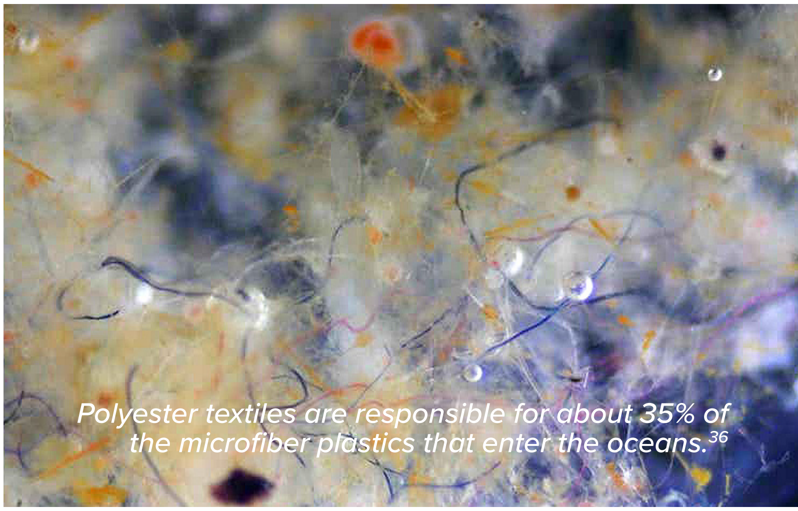
Recycled polyester terephthalate, also known as rPET, is obtained by melting down both post-industrial and post-consumer plastic waste and spinning it into new polyester fiber. Eight soda bottles yield enough fiber for one T-shirt,[31] but recycled plastics contain a mix of toxic chemicals, from antimony to bleach to fire retardants, none of which was designed to go next to your skin.[32]

Recycled polyester has two other main problems:

- **rPET is lower quality:** "Most people believe that plastics can be infinitely recycled, but each time plastic is heated it degenerates, so the subsequent iteration of the polymer is degraded and the plastic must be used to make lower quality products," says Patty Grossman, co-founder of Two Sisters Ecotextiles, in an email to FashionUnited. This means all PET recycling is really downcycling.[33]

- **rPET is still plastic:** Microfibers released during standard home washing range from 124 to 308 mg per kg of washed fabric, depending on the type of washed garment; that corresponds to between 640,000 and 1,500,000 individual microfibers. The most abundant fraction of microfibers shed have dimensions that pass through wastewater treatment plants and pose a growing threat to marine ecosystems.[34] By weight, there will be more plastic than fish in the oceans by 2050.[35]

Industry experts claim rPET progress is promising and the technology is cost-effective today, but



Polyester textiles are responsible for about 35% of the microfiber plastics that enter the oceans.[36]

humans have made over 8 billion metric tons of plastic since 1950 (91% of which has never been recycled) and plastic production has been doubling every 15 years.[36] The fact that the rPET industry isn't larger is an indication of other systemic problems. Even if collection can be done at scale, PET recycling relies on a mechanical sorting front-end that struggles to manage the diversity of fibers and fiber blends present in collected textiles (note: see Section 2, Chemical Recycling).

Roland Geyer, lead author of the study, "Production, Use, and Fate of All Plastics Ever Made,"[37] says, "Just making a bit more effort with the recycling is not going to cut it."[38] National Geographic's piece, "Is a world without trash possible?" made a similar point:

> "In 2015, [circular economy expert Mark De Wit] explained, about two-thirds of the material we scratched from the planet slipped through our fingers. More than 67 billion tons of hard-won stuff was lost, most of it scattered irretrievably. Plastic trash drifted into rivers and oceans; so did nitrates and phosphates leaching from fertilized fields. A third of all food rotted, even as the Amazon was deforested to produce more. Think of an environmental problem, and chances are it's connected to waste. That includes climate change: It happens because we burn fossil fuels and scatter the waste—carbon dioxide—into the atmosphere."[39]

The recycling industry relies on complex and costly reverse logistics and sorting, and this is the point: **nature doesn't sort, it disperses.** Over billions of years of evolution, nature has become optimized for very efficient use of energy. "Surfing for free"[40] using air, water, and soil is how nature moves molecules. Because of that, one wonders why we persist in the Sisyphean task of literally trying to fight against physics.

Circular economy experts are working to create perpetual plastics and emphasize plastic recycling.[41] Dr. Peter Christensen and his colleagues from the U.S. Department of Energy's (DOE) Lawrence Berkeley National Laboratory are one team working towards this goal, and they have discovered a method to return their newly developed plastic to its constituent monomers:

> Recycled plastics are low-value commodities due to residual impurities and the degradation of polymer properties with each cycle of re-use. Plastics that undergo reversible polymerization allow high-value monomers to be recovered and re-manufactured into pristine materials, which should incentivize recycling in closed-loop life cycles. However, monomer recovery is often costly, incompatible with complex mixtures and energy-intensive. Here, we show that next-generation plastics—polymerized using dynamic covalent diketoenamine bonds—allow the recovery of monomers from common additives, even in mixed waste streams.[42]

Unfortunately, there is a pervasive view that benign biodegradation is not compatible with high-quality recyclable plastics, and this has led researchers to neglect biodegradability in their work. "Durability," says Christensen, "trumps the idea [that plastic] should have a finite lifetime." Because closing the loop improves the economics, there is a 10 times reduction in production cost after just one cycle for a closed loop process. However, Christianson acknowledges the reality of thermodynamics when he says his non-degradable plastics will "ultimately meet their demise into the ground."[43] Thus, we return to natural models and recognize that the goods we make ultimately need to be designed for dispersal.

DURABLE MATERIALS IN NATURE

Designing for dispersal does not mean all material must be as transitory as cherry tree blossoms. "Durable" and "safely biodegradabale" can coexist in the same material, and nature shows us how. Bones are stable in our bodies, for example, but degrade in the low pH of soil. And trees in old-growth forests fall so rarely that, even though they decompose very slowly, over decades, they don't overwhelm their environment to become pollution, instead becoming food and habitat. Since so-called "infinitely recyclable" synthetic polymers last for only 10 or so cycles (and most plastics for only two to three cycles) even a long-lasting synthetic polymer must be designed to return safely to the soil, either slowly, like wood, or in response to a chemical switch, like bone.

DESIGNING FOR NATURE'S DYNAMIC EQUILIBRIUM

One of the primary goals of the circular economy is to keep materials in use for as long as possible, slowing their egress to the environment. This is a laudable goal, with the caveat that the laws of physics cannot be avoided: materials always escape. **Whether natural or synthetic, carbon-based or metallic, industrial resource loops exist inside biological ones, not side-by-side. The outermost loop is always the biosphere: air, water, and soil.** It is time to recognize this dissipative flow and work with it, designing the majority of goods for ultimate biological degradation while staying mindful of the toll this takes on the earth. To be sustainable, all industrial processes must be carried out below the maximum rate at which they can occur without degrading the ecosystem in which they reside.

Nature has already solved the problem of the dispersal of wastes (i.e. nutrients) created by the second law of thermodynamics through a material recovery system that spans the entire globe. Therefore, the fastest and most economical way for the fashion industry to transition to a circular economy is to work with nature. There is one huge advantage that the industry has over others in this effort: textiles are all carbon-based. All textiles are dual-purpose, serving a useful purpose as clothing

Soil microbes aid in decomposition and play a critical role in plant health.

For the fashion industry, embracing decomposition may be the inspiration for the innovative new solutions we so desperately need.

but also storing embodied carbon, or energy. For the fashion industry, embracing decomposition to retrieve building blocks compatible with natural primary production may be the inspiration for the innovative new solutions we so desperately need. This is explored further in Section 2.

In a biomimetic fashion economy, the link between decomposers and primary producers is paramount. To be "closed loop," the final degradation product of any material must be of use for either natural or industrial primary production, but it needn't be constrained to the same starting point (i.e., an old shirt does not need to become a new shirt or even textile). And because primary production always requires energy, that energy must be renewable. The second law also means no material loop can ever be completely isolated from the biosphere, and so, to avoid bioaccumulation, any material in use must not pollute when it inevitably escapes. **This means there is no alternative to the phasing out of non-compostable materials like polyester, and new fibers, however "recyclable," should not be developed if there is no natural decomposition for them.**

In the future, all fashion industry loops (technical and biological) could cross and mingle, enabled by the use of universal building blocks. Such a system requires the existing (and hard won) recycling and circular economic infrastructure to enable consumption to be highly efficient, extracting all available usefulness from materials before they are ultimately safely decomposed. No flows begin or end in the soil, air, or water, and a stable equilibrium is able to emerge.

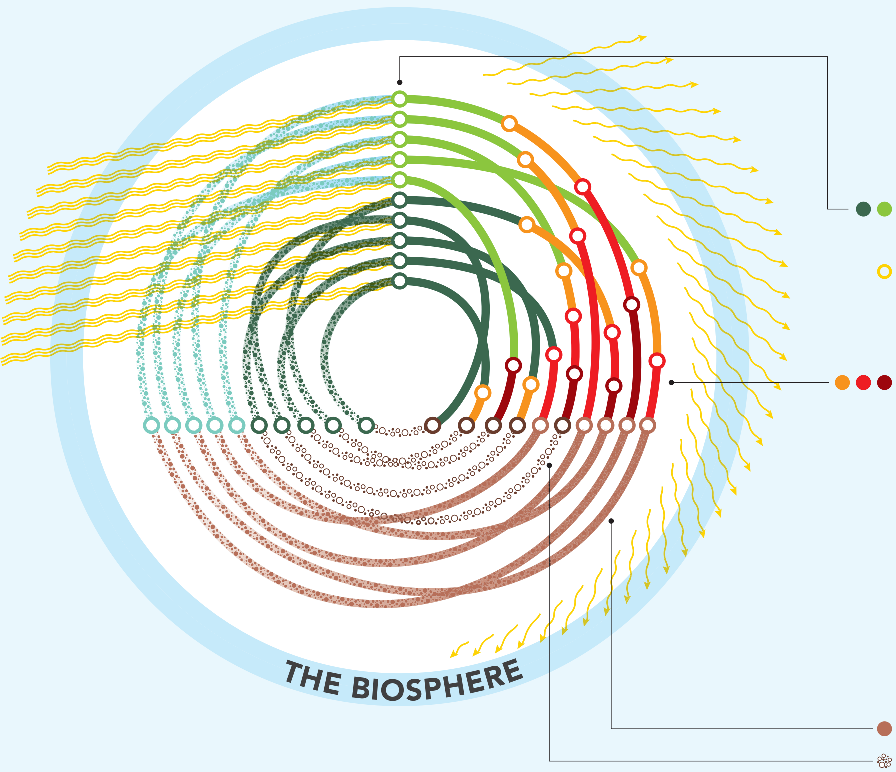
To create a fashion ecosystem consistent with the laws of nature is, to quote Bill McDonough, "our new design assignment."[44] Concluding this section, we see that the laws of physics ensure polyester, even when recycled, will ultimately be a pollutant.

Next, we will point to the many indicators showing natural and bio-based fibers are not only viable but achieve several all-important functions of nature: carbon sequestration, regional health, and restoration of biodiversity and soil health.[45,46]

Figure 3.

Biomimetic Fashion Economy

In the future, all fashion industry loops (technical and biological) could cross and mingle, enabled by the use of universal building blocks. Such a system requires the existing (and hard won) recycling and circular economic infrastructure to enable consumption to be highly efficient, extracting all available usefulness from materials before they are ultimately safely decomposed. No flows begin or end in the soil, air, or water, and a stable equilibrium is able to emerge.



We can design a biomimetic flow of energy and materials through industry:

Primary Production
Diverse feedstocks replace petroleum. **Fibercrops** combine with **biosynthetics** made via fermentation, all powered by **renewable energy**.

Consumption
Materials are bio-available and recyclable. **Reuse, remanufacturing and recycling** capture the full value of materials and slow the outflows to avoid overloading local recovery infrastructure. Processing is powered by **renewable energy**.

Decomposition
Recovery is distributed and scalable to match the global fashion economy, returning all textiles to their basic building blocks.

Robust **compost** systems are supported by **chemical recycling** and **gasification**.

SECTION 2

Moving to a Regenerative System

"The industry's answer to complex sustainability issues has been to reinvent certification schemes… which often don't deliver the intended results. So we switched tactics and are investing in regenerative agriculture…. We will still use certifications where beneficial, but we are going to measure success through biodiversity, soil fertility, and thriving ecosystems."[47]

Megan Meiklejohn, Sustainable Materials & Transparency Manager, Eileen Fisher

The volume of natural fiber produced has remained remarkably static since the invention of polyester fibers in the 1940s, despite the global population more than doubling.[48] The gap in production has been filled with synthetic fibers, largely manufactured from petrochemical feedstocks. Meanwhile, producing natural fibers through industrial means is also petrochemical-intensive and environmentally damaging,[49,50] and processing and dying technologies all have considerable negative environmental impacts.[51] In The Pulse of the Fashion Industry report, the fibers of the future considered least environmentally damaging are recycled polypropylene and polyester,[52] but as shown in Section 1, this is not a sustainable solution. We are already exceeding planetary boundaries for phosphorous and nitrogen flows[53] (see Fig. 4) and are at increasing risk to exceed several others if existing practices continue, including a reliance on natural fibers.[54] Yet how can we be so bold as to suggest moving to an entirely biological-based system, which inevitably involves land use?

First, we need a shift in thinking away from the efficiencies of centralized manufacturing to the resilience of decentralized, regional production, where local impacts can be measured against planetary boundaries.[55] In both natural and human systems, for a system to be optimized, there needs to be a balance between efficiency and resilience.[56] Currently, the fashion system (and the systems it relies on for material and capital inputs) is quite efficient but not very diverse. That makes the system extremely brittle. As diversity in the system increases, so does resilience (see Fig. 5). And for natural ecosystems, which fashion relies on, as biodiversity increases, so does resilience, primary productivity (more biomass), and ecosystem health.[57,58] What emerges from nature's lessons, regardless of scale, is the prime directive not to foul one's own nest. New levels of environmental restoration, biodiversity promotion, and the return of fair local jobs all become possible when we shorten the supply chain.

"Negative trends in nature will continue to 2050 and beyond in all of the policy scenarios explored in the Report, except those that include transformative change…"[59]

IPBES Global Assessment 2019

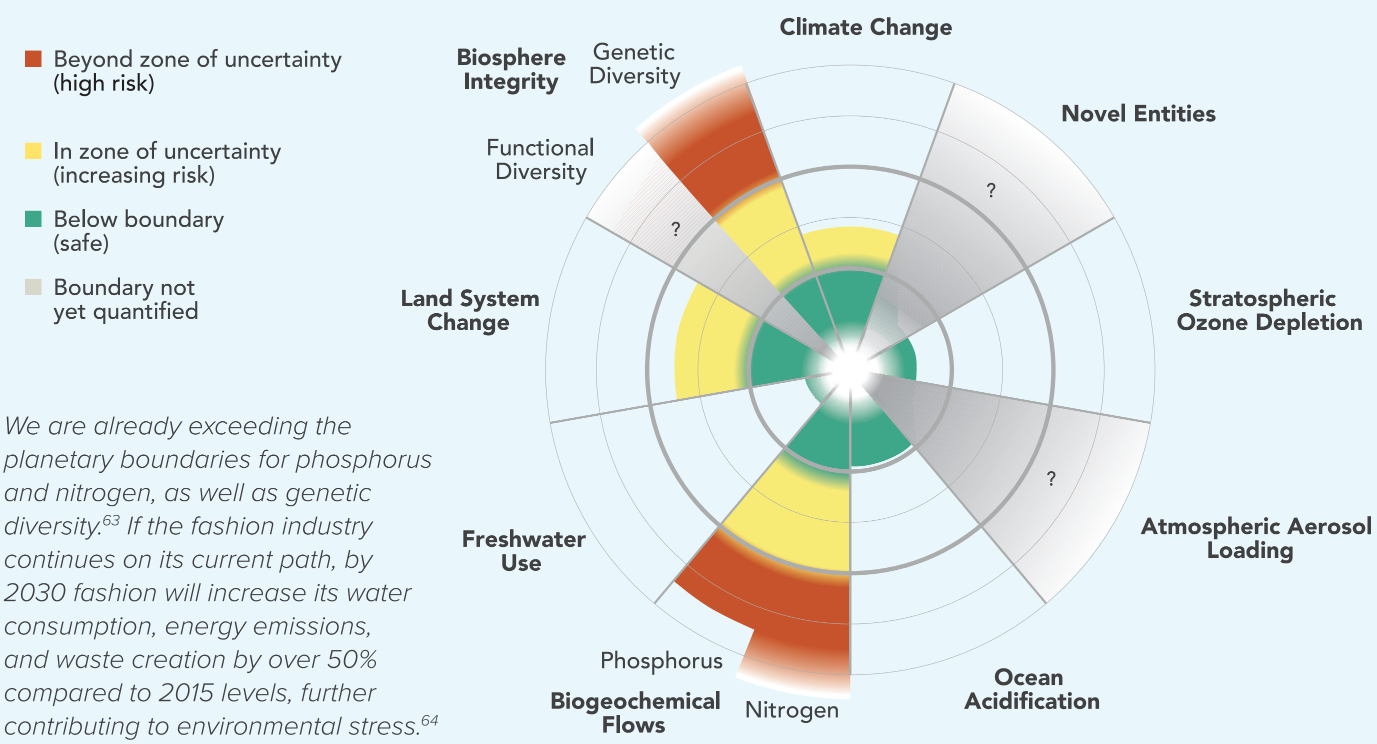
Second, we need to embrace new technologies for fiber production, aligned with nature's cycles, in ethical and sustainable ways. These technologies include fermentation and gasification, as well as new spinning technologies.

Third, by reducing waste, the amount of land needed to produce bio-based textiles will decrease. We need to focus on waste in both the food and fashion industries, since both systems are inextricably linked,[60] relying on farmed and forested land for production and typically contributing to humanity's exceeding the planetary boundaries. Approximately one-third of all food intended for human consumption is wasted,[61] while fashion produces a huge amount of pre-consumer waste due to excessive inventory that is never sold and waste generated on the cutting room floor (approximately 60 billion m^2 annually, or 15% of total production).[62] Many people and organizations are already addressing how to minimize waste in these two sectors.

Below we will focus on how decentralized production is possible and show that we already have what we need for the resurrection of bioregional fashion, including opportunities for utilizing waste for primary production. Bioregional fashion does not mean that all fashion must be locally constrained in terms of manufacture but rather that the inputs of fashion are bound by the carrying capacity of specific ecological zones and fashion is produced locally where appropriate.*

Figure 4.

The Planetary Boundary Framework



We are already exceeding the planetary boundaries for phosphorus and nitrogen, as well as genetic diversity.[63] If the fashion industry continues on its current path, by 2030 fashion will increase its water consumption, energy emissions, and waste creation by over 50% compared to 2015 levels, further contributing to environmental stress.[64] Illustration source: Steffen et al. (2015).

* *The City Portrait, a tool for downscaling and applying Doughnut Economics regionally, could be used to assess options for thriving people and the planet, locally and globally. See: https://www.kateraworth.com/2020/04/08/amsterdam-city-doughnut/*

WHY ACT REGIONALLY: THE BIOLOGY

Natural systems are synonymous with biodiversity. In nature, the wider the variety of species at a location, the healthier that ecosystem is.[65] As ecosystems develop and become more complex, the number of interactions between various species increases, and more niches—a combination of a species' physical habitat and functional role—become available.[66] For example, a mature forest contains trees of varying heights and sizes which form a photosynthetic canopy. Shrubs take advantage of any sunlight not absorbed by the leaves above. Ferns and mosses benefit from any remaining useful light, occupying distinct microniches based on the precise microclimatic conditions and available water, nutrients, and sunlight.[67] A single ecosystem contains a vast array of different possible niches with colonies of different organisms overlaid and intermingled. Far from reducing opportunities through competition, as ecosystems develop and grow in complexity and intricacy, there is a corresponding increase in the flow of energy through the system. When the whole flourishes, there is greater abundance overall and more for all.[68]

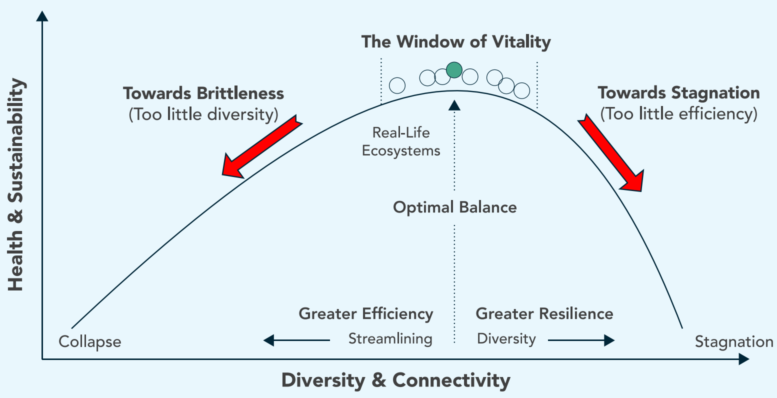
A patchwork of local fibers only makes sense in the context of regenerative agriculture, making better use of already-cultivated land and restoring degraded land rather than developing new land or forests. This may mean sacrificing some efficiency in order to have greater resiliency. Yet when the metric of appropriate feedstocks becomes soil health, then biodiversity and a cascade of environmental and social benefits will follow.[69, 70, 71]

THE TRANSITION TO 100% BIODEGRADABLE FIBERS: PRIMARY PRODUCTION

Despite fashion's reliance on synthetic fibers, biological fibers continue to make up 38% of global fiber production, primarily in the form of cotton and man-made cellulosic fibers. Based on our preliminary research, we believe fashion can both meet global apparel needs, including desired performance characteristics, and readily transition to 100% compostable fibers from three sources: natural fibers, cellulosic feedstocks, and fermentation products. The exact proportions and investment required to make such a shift will require future research, together with industry and economist partners (see Section 3). What follows

Figure 5.

Measuring Network Health Using the Balance of Resilience and Efficiency



Healthy systems maintain a balance of resilience factors (small, diverse, flexible & densely connected) and efficiency factors (big, streamlined & powerful) within a Window of Vitality representing optimal network health.[72] Goerner et al. (2015).

is an indication of the fiber classes that could meet or exceed production currently filled by synthetics, including natural fibers, fibers from cellulosic waste, fermented fibers and, as transitional technologies, fibers produced through chemical recycling and gasification.

SOURCE 1: Regenerative farm and fiber systems could account for 23 billion one-pound garments (US alone)

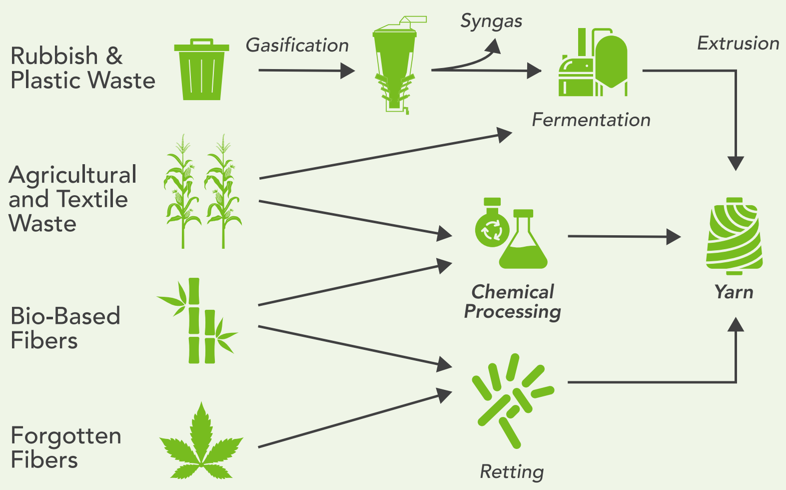
The most proven feedstocks for a sustainable fashion industry are the natural fibers that have been used by humans for millennia, including cotton, wool, flax, hemp, ramie, and abacá. Research and development towards improving breeding, growth, and processing of these fibers has been minor given the rise of synthetic textiles, but they play an important role in a regional, restorative, bio-compatible fiber system.

In part, regenerative agriculture means that animals must be integrated into cropping systems in order to provide fertilizer and mimic the functions of wild grazing herds. Natural fibers grown using regenerative agricultural methods can build soil, sequester carbon, enhance biodiversity—both above and below ground—support other ecosystem services, and contribute to bioregional economies all at the same time. “[Regenerative agriculture] is something that could create and will create the future of sustainability,” claimed Rachel Lincoln, Prana’s Sustainability Director, in an interview with Fashionista.[73] In addition to many fashion brands recognizing the benefits to ecosystems and the planet, regenerative practices also result in higher-quality fibers and leathers, according to another interview with Géraldine Vallejo, Kering’s Sustainability Programs Director.[74] As the culture moves towards fewer, higher quality goods, the higher integrity of these materials is important.

Figure 6.

Developing Locally-Appropriate Feedstocks

We can use this ecological principle to help design scalable and resilient supply chains if, instead of thinking about transporting a limited array of fibers around the world, we think in terms of a patchwork of local industrial niches. No feedstock should be extracted at a rate greater than the carrying capacity of its region, and a diverse cohort of different fibers is needed. Any technology ultimately relies on natural resources as a feedstock and, however environmentally sound, there will be a hard limit on the amount of that feedstock that can be sustainably grown or extracted. A diversity of feedstocks, adapted to place, is crucial, as there is not a single new fiber source that can or should scale to equal petrochemical-based fiber production.



Natural fibers already feature many performance features, including odor wicking, great thermal properties, and water shedding.[75, 76] Recent attention to natural fibers is expanding their potential. Fibershed has shown that combining wool with hemp, for example, allows for machine-washable garments that resist shrinkage. Both Seff and StexFibers have developed techniques to soften hemp fibers, allowing them to be used in high-end textiles.[77] Redirecting the human ingenuity, knowledge, and capital that is currently so focused on improving the performance of synthetics to the processing and performance of natural and bio-based fibers could rapidly accelerate development, allowing more regional niches to be filled, and expand the desirability of and demand for natural fibers by designers, brands, and consumers.

> ***"If we converted all global croplands and pastures to regenerative organic agriculture we could sequester more than 100% of current annual CO^2 emissions."*** [78]
> Rodale Institute

Polyester currently has a cost advantage rooted in oil subsidies, scale, and decades of invested R&D. By shifting those economic drivers and increasing R&D, the industry can make natural fibers cost competitive. There have been definitive innovation inflection points where the price of natural fibers dropped dramatically (e.g., the invention of the cotton gin). As most natural fiber processing has remained unchanged for decades, it is foolish to dismiss natural fibers as too expensive without exploring the potential of new developments. An example is color-grown cotton.[79] Its autumnal hues of amber, yellow, and khaki green are frowned upon by cotton processors who want to avoid cross-contamination of white fibers and don't want to clean their equipment between shipments. But colored cotton avoids toxic dyes and accompanying water use, and its non-transferable color only gets more intense with each home washing. It is naturally soft and has a

THE BOUNTY OF INTEGRATED SYSTEMS

Although the fashion world has recognized the need for a sustainable materials mix, it has not made a hard commitment to phasing out synthetics, and has yet to invest in a systemic exploration of how diverse bio-compatible feedstocks could meet the textile industry's needs.[80, 81]

Fibershed, an NGO based in the U.S., has been an active proponent of exploring the potential of natural fibers as part of integrated, restorative farms and communities. Based on initial experiments, Rebecca Burgess, Fibershed's Executive Director, has written:

It could be fairly easily assumed that [an] integrated agricultural system would healthfully yield wool, hemp, wheat, lamb and dairy, and would generate an additional 112 million tons of natural fiber per year in this country (US) alone, without converting any additional land to agriculture. That could equate to approximately enough fiber to produce twenty-three billion one-pound garments (assuming weight losses to the fiber throughout the milling process). [In the U.S.], we don't consume that many garments per year, which in turn means that we would have ample room within this scenario to reduce the acreage planted with hemp significantly and still produce enough natural fiber to clothe everyone in the country with compostable, organic and non-toxic garments.[82]

pleasant scent, adding to the list of attributes that don't have to be added chemically. Considered holistically, naturally colored cotton could be a business opportunity large enough to justify an initial investment in new processing and manufacturing that could drive price parity with polyester.

SOURCE 2: Cellulose agricultural waste alone could meet 2.5 times the current global fiber demand

A second class of natural feedstocks for biodegradable fiber production is the wide variety of plant-based materials available as the starting point for producing lyocell and viscose/rayon and other man-made cellulosic fibers. As with natural fibers, however, scale and sourcing matter as much as the fiber chemistry and production method, and unfortunately there are numerous examples (as tracked by Canadian NGO Canopy) of the cellulose for viscose manufacture being sourced from old growth and endangered forests in order to meet the scale requirements for a global supply chain.[83] If only there were an abundant, cellulosic waste stream...

Circular Systems™ is taking a holistic approach with Agraloop™ Biorefinery, winner of the 2018 H&M Global Change Award. Their technology transforms agricultural waste into a new "natural" fiber, useful for yarn, paper, and textile manufacturing. With a platform of technologies and through "virtual vertical integration," they ensure their commitment to regenerative technologies is carried throughout the value chain. Circular Systems claims that six crops alone—oil-seed hemp, oil-seed flax, banana, pineapple leaves, rice straw, and sugarcane bark—**currently offer more than 250M tons of fiber per year, or enough to meet 2.5 times the current global fiber demand.**[84] The system also produces organic fertilizer and, by removing plant waste that would otherwise be left to rot or be burned, they also reduce agricultural greenhouse gas emissions and deaths from air pollution (5% of which are attributed to biomass burning globally[85]). Other companies, such as Spinnova and Bastcore, are also making holistic use of agricultural plants, and regional development of similar technologies would go a long way towards addressing existing waste streams without the need for developing any new land.

Agraloop™ BioFibre™ used to make clothing.

Planting forests and other crops for natural fiber production could also play a critical role in helping restore the two billion hectares of degraded land globally[86] without competing with existing agricultural land. Doing so would also help sequester carbon and restore other ecosystem services to the degraded lands.

SOURCE 3: Fermentation

Fermentation is a process where microbes such as bacteria or yeast are cultured in a process similar to beer making. Biological building blocks produced through fermentation are the final class of feedstock for textile primary production. The fermentation process is clean and well suited to bioregional production, as microbes can be fed using a diverse stream of non-cellulosic waste from other industries, including the food industry. Fermentation is a predictable, agile approach with potentially low barriers-to-entry and quick start-up potential (as shown by the prevalence of microbreweries). New developments in this ancient technology mean fermentation is gathering pace as a method for fiber production, with a number of biotech startups having reached a significant level of technological readiness (Appendix C).

In order to take advantage of the considerable potential of fermentation to rapidly fill the shortfall in fiber production left by a move away from synthetic fiber, it is important to keep in mind the certainty that materials produced using this method will escape into the environment.* That is, we must not use fermentation to produce non-biodegradable fibers. Additionally, the feedstock for fermented fibers is not yet a clear sustainability advantage. “We have to remember that fermentation is tied to carbon, which currently comes from sugar,” says Natsai Audrey Chieza, founder and director of Faber Futures. “We have to look at sustainability in terms of the input.”[87]

THE TRANSITION NEEDS DECOMPOSITION

In nature’s dynamic equilibrium, decomposers are just as important as primary producers. In a world without decomposition, plants and animals would lie where they fell at the end of their lives, with all the energy and nutrients in their tissues frozen forever in place. It would not take long for the nutrients needed for new life to run down, and for the dynamism of nature to fall still. The current fashion industry does not design with decomposition in mind and therefore is largely missing its decomposers. The rapidly rising tide of ocean plastics is an expression of the trapping of once-valuable resources in useless forms caused by the absence of this key participant.

Until all fibers are designed for benign biodegradability, we need transitional technologies to fill the decomposition gap.

TRANSITION SOURCE 1: Chemical Recycling

Chemical recycling of fibers has seen significant research and development in recent years, and the technology can handle a wide range of fibers/blends. This process is closer to what nature does in a few key ways. Unlike rPET, the products of chemical recycling are the same quality as virgin feedstocks, and they are also of use in primary production across a variety of industries.[88, 89, 90] It is a technology that recreates the links between decomposition and primary production and does

ALLBIRDS is a San Francisco-based sustainable shoe company with a similar price point to other sneakers. Allbirds produces the upper for its shoes from Merino wool and the foam sole through fermentation. Upon his first experience using fermented micro-algae to create polyurethane foams, co-founder Joey Zwillinger said, “It clued me into the fact that there’s so little focus paid to innovating around natural and/or sustainable raw materials in a consumer landscape. There was a big opportunity for brand building and marketing sustainable, high performance products.”[91]

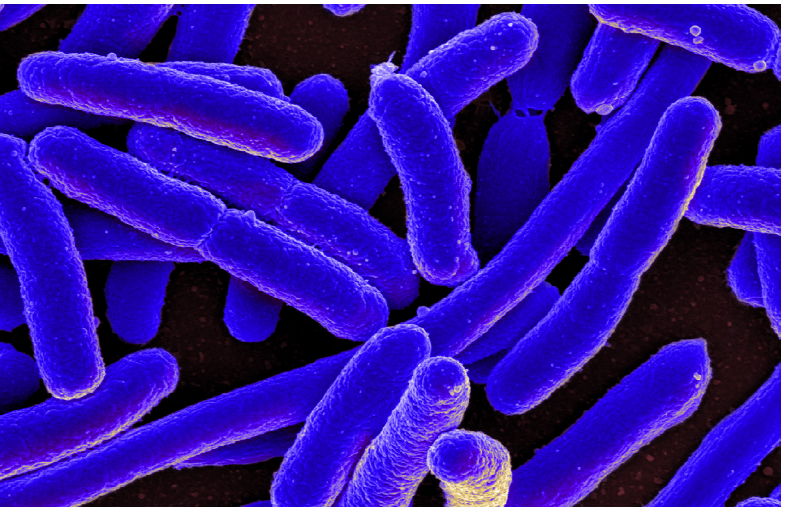
* *Fiber production via fermentation relies on genetically modified organisms, and it may be wise to consider the risks prior to wide adoption of such technologies. In the case of the microbes used in fermentation to produce fibers, the risks are low: the organisms themselves are harmless and usually highly attenuated, meaning they cannot survive outside the highly calibrated and supportive environment of the facility; the process of purifying the target substance destroys and removes the organisms from the product; and any equipment used can be easily sterilized using only steam and high pressure. These techniques are very well understood and have been in use safely in laboratories for over a century. However, in some of the new processes, the organisms are integral to the product and are fixed to the fabric and killed in situ rather than removed, and still others are considering products that include live microbes. In these cases, the precautionary principle is required.*

so to produce a more widely useful building block. In this context, the reverse logistics and sorting needed is more limited, and the results are more useful than those from conventional recycling. After interviewing experts across a broad spectrum of textile industries, GreenBlue concluded that new chemical recycling technologies require relatively little energy input and "have the potential to operate more efficiently as a distributed network of small-scale facilities near sources of PET feedstock."[92]

TRANSITION SOURCE 2:
Gasification + Fermentation

Energy recovery through incineration converts synthetic fibers like polyester to carbon dioxide of use to natural primary producers in photosynthesis. In this regard, it closes the loop and might be considered a form of industrial decomposition. However, nature's dynamic system is an equilibrium and to maintain it, the amount of cycling carbon must remain constant. When we burn petrochemical-based synthetic fibers, we release greenhouse gasses that were previously safely locked under the ground.

Until now, the importance of decomposition for closing resource loops has been missed, and so there are relatively few sustainable technologies available. An arguably even more interesting industrial decomposer than chemical sorting is gasification, where any carbon-based waste can be subjected to a very high heat (without burning) that converts it directly into carbon dioxide, carbon monoxide, and hydrogen gas.[93] Unlike incineration, the gas mixture (syngas) is of value in its own right as a fuel, and it can also be used as a raw material for fermentation by methanotrophic bacteria.



Methanotrophic bacteria utilize the products of decomposition as food.

Methanotrophic bacteria consume methane directly, using it as a food source, and they can also consume carbon monoxide and carbon dioxide. At least two companies (LanzaTech and Kiverdi) have already recognized the potential for gasification and fermentation to generate a wide variety of substances of use to humans, including feedstocks for manufacture of compostable synthetic fibers. Because the bacteria "eat" the gasses, they are not vented into the atmosphere to contribute to global climate change. This raises the exciting possibility of fiber mills and waste dumps existing side-by-side, with virgin production of high-value fibers fed directly by mined landfill waste, or by microplastics filtered from the ocean. With such a process, there is no risk of toxic leachates from rPET ending up close to people's skin, and the new fibers produced can be designed to safely biodegrade. Together, gasification and fermentation by methanotrophic bacteria link decomposition to primary production and are able to bring an existing pollutant back into use. Combined, they could be a cost-effective and ecologically safe way to digest the existing mountain of waste polyester.

That said, this is a transitional technology and does not mean we can keep designing with fossil fuel-based synthetic fibers due to their other negative environmental and human health impacts, which occur from the extraction stage through the use and resulting microplastic shedding stage.

The above section shows, at a high level, how a future fashion industry might structure production in order to sustainably source biocompatible materials at scale, and why doing so is so important. It also highlights some transitional technologies to help us deal with our existing textile pollution. In section three, we propose a set of concrete recommendations for how industry supporters can facilitate the necessary changes to new modes of production as rapidly as possible.

“The more our world functions like the natural world, the more likely we are to endure on this home that is ours, but not ours alone.”[94]

Janine Benyus, author and co-founder of the Biomimicry Institute and Biomimicry 3.8

SECTION 3

Recommendations

In this section, we offer next steps and recommendations to the investors, funders, and fashion brands that will enable a new fashion ecosystem to thrive and flourish.

1. Conducting further ecosystem research. Step one of defining the future of fashion is the difficult recognition that plastics do not belong in the biosphere and how we might replace them with fibers that support a natural equilibrium. But there are many ecosystem lessons that have not yet been explored or should be explored more deeply: adaptive cycles, diversity and resilience, designing for durability and disassembly, cooperation, the role of interdependency, ecosystem succession, and more. For a list of this work, see Ecomimicry[95] and Appendix B.

2. Defining the criteria for net-positive investments in the new fashion economy. The need for new business models and ways to change price point tolerance for customers are two of the biggest issues identified in The Pulse of the Fashion Industry report.[96] While our paper does not explore new business models, per se, some investment indicators are identified below. How quickly and with what level of investment can we replace synthetics with cellulosic waste, what percentage of farmland can be quickly converted to regenerative practices, and how quickly can we scale benign fermentation from gasification waste and other waste products? Relatedly, an equally important exercise will be to define the boundaries of synthetic biology, an area already getting significant investment. We look forward to working with other biologists, along with conservation, land, agriculture, and economic analysts to help define appropriate criteria for investors.

3. Supporting existing efforts in sustainable (responsible, regenerative) fashion. Even with the number of reports we read and leaders we consulted, we only scratched the surface of analyses and progress being made by organizations that share our same goal. We hope to join stakeholders and formulate pilot efforts to test some of the more difficult aspects of this report. There are many big brands, specifically in athleisure, with a goal to be petroleum-free within the next decade.[97] Putting the burden on customers to demand this change is unfair (that said, we think the timing is right for an awareness campaign), as designers shape the choices on the market. Our hope is to support the brave brands willing to embrace the idea that nature has demonstrated it can achieve any function that humans desire. By bringing biological intelligence to polymath teams of green chemists, material scientists, mechanical engineers, and natural fiber experts, we can support future-forward organizations.

LEVERS FOR CHANGE

Here is a beginning list of priorities for philanthropic support and for grant and impact investment opportunities. One critical lever not addressed here is the role of regulation and government, but that topic has been well-covered by our colleagues in the conservation sector and other circular economy leaders.

LEVER 1: Invest in local cycles

Regional development is more than local manufacturing: it's the full cycle of production, consumption, and decomposition, using renewable energy, to become more resilient to external shocks. Global mass production has led to the near disappearance of smaller-scale regional manufacturing. With the exception of 3D printing, there has been minimal recent investment in innovation in smaller machinery, yet these low cost investments can yield economic and fiber security. While we have seen some large-scale investments in synthetic biology (e.g. Bolt Threads raised $200M in venture funding), simple, small-scale proven investments are often difficult to fund (e.g. replacement of local yarn-spinning equipment costing $65K by Fibershed).[98]

New regional production should be appropriate in scale, transparent in structure, and designed to benefit its community in a way that lifts all boats.[99]

- **Repair and upgrade equipment:** Somewhere between the 200-year-old cotton gin and 3D printed footwear[100] is a real market need for working with various feedstocks. Microfinancing for equipment purchases and repairs is a cost-effective jump-start to support regional production. Engage regional university engineers in making new degumming equipment, yarn spinners, and weaving machinery (that may end up informing next generation printers, as well). Look to biological models to inform new levels of efficiency and performance fibers.[101]
- **Catalog of regional waste streams:** Work with local waste management and government bodies to inventory all locally produced cellulosic and sugar waste streams available for input into fiber production.
- **Create industrial symbioses:** Co-locate new bio-driven technology facilities near waste streams (see Agraloop and Kiverdi, above, and John Todd's Intervale Eco-Park[102]). Define regional boundaries with tools from Doughnut Economics[103] and Biomimicry Factory as Forest[104], which evaluate a project based on intact reference habitats and planetary boundaries.
- **Send the pattern, not the clothes (or even the machines):** Invest in design commons and peer production initiatives that design globally and manufacture locally (DGML)[105,106] This distributed design scenario is already in place to some degree with 3D printed footwear and in the built environment.
- **Focus on the whole value chain:** Creating incentives for regionally scaled processing infrastructure, such as non-toxic dye houses and wet processing equipment that meets strict water regulations, is essential to creating a regional fiber economy.[107]

LEVER 2: Build restorative and regenerative agriculture systems

Transitioning to a sustainable fashion system is inextricably linked to sustainable agriculture and restoring degraded lands. The goal is not to replace the 60% of synthetic textiles entirely with virgin natural fibers, but when bast fibers, cotton, rayon, or animal fibers are being produced, to be sure they are produced in the context of regenerative agriculture:

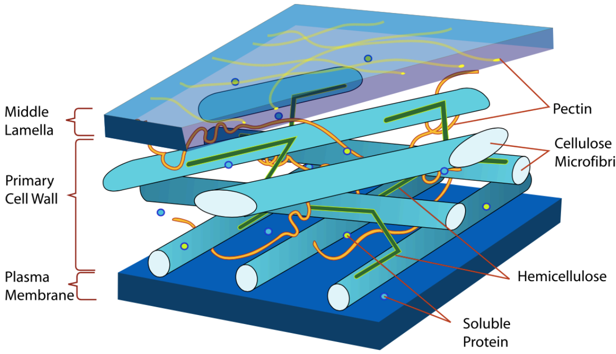
- **Conservation pays:** a USDA-funded study by Delta Institute, Farmland LP, and Earth Economics demonstrated $21.4M in net ecosystem value ($12.9M direct benefits and $8.5M in avoided damage) on 6,000 acres over 5 years using regenerative farm management practices at scale.[108] More studies quantifying the value of regen agriculture are needed.[109]

- **Restoring degraded lands pays:** We've taken away the biodiversity repository necessary for many degraded lands to heal on their own without decades or more of time. Restoring degraded lands has great potential to create fiber, food, and jobs. In Latin America and the Caribbean alone, for example, restoration projects could yield $23 billion over a 50-year period. More investment in restoration for sustainable fiber production is needed.
- **Cluster fiber research and demand:** Bast, fruit, and seed fibers have both woven and non-woven applications,[110] and also serve as new feedstocks for fuel and polymer composites.[111] Right now fiber research is pursued independently of these other sectors, but circular economy consortia can help aggregate these efforts. For example, Ford, Nike, P&G, Heinz, and Coca-Cola have come together to form a pre-competitive Plant Technology Collaborative.[112]
- **Fund new research:** Create a series of regional, small-scale funds to support fiber system entrepreneurs' prototyping with domestic fibers.
- **Create new funding vehicles:** Provide long-term financial support for farmers to implement regenerative farming and agroforestry and to integrate diverse planting and animals into cropping systems, building soil and increasing biodiversity.[113]

LEVER 3: Incentivize creation of new biomaterials

For any performance gaps not met by natural fibers, what's needed are new materials that can offer the same stretch, durability, repellency, and more that petroleum-based products can. Innovation around common performance needs like color and stain repellency has already begun, and fermentation is beginning to have an impact here as well, with numerous companies well on their way to delivering alternatives to petrochemical-based dyes (Appendix C). We anticipate all performance needs can be achieved with bio-based feedstocks but not before critical attention and definition is put on synthetic biology and nanomaterials.

- **Biomimetic biomaterials:** Engage university students in design and material science to create new biomaterials based on biological models, like bull kelp which stretches without breaking due to the orientation of its fibers.
- **"ComPost Modern" design challenge:** Fund and launch a global competition around decomposition and the system conditions necessary to make decomposition successful. This is a largely overlooked aspect of closing materials loops that we believe holds great promise for inspiring new technologies and business models.
- **Advance the knowledge commons:** Further invest in data commons initiatives like ChemFORWARD[114] and ZDHC[115] that enable researchers and practitioners to share knowledge, collaborate, and co-create.



Bull kelp could be a model for creating a stretchy biomimetic biomaterial.

In writing this report, we went all the way back to the first of all principles: the laws that run the universe. We looked hard at how natural materials cycle, and why. At first, we were concerned that we would need to suggest research into new technologies and fibers that could take decades to develop, but the more we looked into it, the more excited we became. As we collated a list of startups, new technologies, and ideas (Appendix C), we realized that, far from needing further research, we could recommend concrete actions for all actors in the industry to take today.

And then, two-thirds of the way through the project, we found ourselves in the midst of a pandemic. The conclusions of this report are unaffected by COVID-19—they are based on the second law of thermodynamics and deep observations of nature, and these things are unaffected by human illness. But one thing has been altered irrevocably: no one can ever claim again that we cannot turn the global economy on a dime when we have to. What might local food, mask, and glove supply chains have looked like if food and fiber were intercropped to buoy security for both? If bacteria used to create silk-like fibers could also create something more like latex? This is the adaptability and resiliency that nature, albeit on a human timeline, can help provide.

The time for acting is now.

Appendix A: List of Industry Publications

Buchel, S., Roorda, C., Schipper, K., Loorbach, D. 2018. The Transition to Good Fashion. Drift for Transition.

Ellen MacArthur Foundation. 2017. The New Plastics Economy: Rethinking the future of plastics & catalysing action.

Ellen MacArthur Foundation. A new textiles economy: Redesigning fashion's future, 2017. http://www.ellenmacarthurfoundation.org/publications.

Global Fashion Agenda. CEO Agenda 2020. https://globalfashionagenda.com/ceo-agenda-2020/

Global Fashion Agenda & The Boston Consulting Group. 2017 Pulse of the Fashion Industry.

Metabolic. 2014. Textile Sector Analysis: Trends, Impacts, and an Outlook on Circular Economy.

Quantis. 2018. Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries study.

The Business of Fashion and McKinsey & Co. 2020. The State of Fashion 2020.

Appendix B: Table of Intervention Points

Category	Intervention Points	Biological Functions and Research Areas	Questions / Challenges
System	Improve feedback, share information, certify, establish chain of responsibility	Cooperate and/or compete • Social groupings • Freeloaders & mimics Feedback loops • Local vs long distance communication • Calcium signalling • Single genetic code • Bacterial plasmids • Immunity Demonstrate fitness • Sex-linked morphology	• Are the current feedback loops adequately drawn? Should they be cross-sector, geographic, with an emphasis on air, water, and soil? • Cooperation between whom? Aggregating supply around the wrong materials, even if fully disclosed, gets us nowhere. • When is certification/best practice guidance useful? • Is there a role for IP? • Why are so many initiatives not working?
Materials	Develop new textiles, develop/use renewable inputs, new manufacturing and dyeing processes, additive manufacturing	Color Manage resources Heal Grow/build • Specialized vs modular/standardized	• Do we need transparency if everyone is using the same beneficial palette? • Do CHON/natural fibers equate to biodiversity, responsible land use, and biosphere repair?
Cleaning up the existing mess	Recycling, implement clothing collection at scale	Concentrate distributed resources (entropy!) Use energy • Trophic levels Manage waste • Plastic-eating bacteria	• What are the priority areas for ecosystem repair (eg: what elements of a new fashion industry clean up pollution)? • Is polyester in endless loops really the best answer? • If industry is using biorestorative materials, is recycling necessary?
Resource use	Oversupply, increasing utilization, improving efficiency, slowing resource loops, rental models	Respond to local conditions • Microclimates • Efficiency vs resiliency • General vs specific Manage supply • R vs K strategies • Durable vs ephemeral • Resource cycling velocity • Seasonality	• When is being frugal better (eg: cactus in the desert vs cherry blossoms) • Is durability always better? (eg: durable vs. ephemeral elements in nature) • Do we need greater efficiency if energy is clean? • When is slowing resource loops better and when does accelerating loops equate to faster regeneration?
Switching systems	Role/impact of large multinationals vs small disruptors, industry associations, new business models	Adaptive cycle/ecosystem dynamics Adapt to new conditions • Pioneer species • Ecosystem succession • Cambrian explosion Maintain existing ecosystems • Keystone species Make decisions • Bee/consensus decision-making	• What is the influence of size and responsiveness of stakeholders? • Do we need to agree on the direction (“broad stakeholder buyin”) for change to happen?

Appendix C

NATURAL FIBERS/DYES AND REGENERATIVE AGRICULTURE

- **BastCore's** wet process transforms coarse raw bast fiber into soft white cotton-like fiber for textile applications. BastCore is also developing products that use the core or hurd of the hemp stalk, providing an additional economic benefit to farmers. https://bastcore.com/

- **Botanical Colors**, based in the US, supplies artisans and industry with the materials and know-how to dye textiles in a way that uses less water, is non-toxic and biodegradeable, and draws its incomparable color palette from humble plants and natural sources. All colors are sustainably derived, many from agricultural and food waste products. https://botanicalcolors.com/

- **The Campaign for Wool** encourages collaboration between an international community of woolgrowers, major fashion designers, retailers, manufacturers, artisans and interior designers, in order to educate consumers about the versatility and myriad uses of wool.

- **Cotton of the Carolinas** is a t-shirt brand that demonstrates the bioregional approach. Every step in the production process happens within a 600 mile (1,000 km) radius. https://tsdesigns.com/cotton-of-the-carolinas/

- **Fibershed** is a US-based NGO that develops regional fiber systems that build soil and protect the health of our biosphere. The organization also has an international Affiliate Program. https://www.fibershed.com/

- **Green Nettle Textile** is a Kenyan-based company that converts nettle stalks into a linen-like fabric, dyes it with natural plant dyes, and employs thousands of artisans across the globe. A 2019 Global Change Award winner. http://greennettletextiles.com/

- **Organic Cotton Accelerator** is an organization that brings together stakeholders across the industry and creates the conditions for organic cotton to thrive. https://www.organiccottonaccelerator.org/

- **The Linen Project** investigates and seeks to reactivate the economic viability of flax cultivation and small-scale linen production in the Netherlands, with a view to broader international relevance. https://craftscouncil.nl/en/the-linen-project-2/

- With 100 global hubs, the mission of the **Savory Institute** is the large-scale regeneration of the world's grasslands through Holistic Management to address the global issues of desertification, climate change, and food and water insecurity. https://savory.global/

- **Stex Fibers** has developed a technique to soften hemp fibers, so they can be used for high end textiles. The company has proven the basic technical concept at lab scale and built a test unit at Industrial Park Kleefse Waard in Arnhem, The Netherlands. https://www.stexfibers.com/

- **Stony Creek Colors** makes clean and safe US-grown natural colorant for the textile and fashion industry and is best known for Tennessee-grown natural indigo for denim. https://stonycreekcolors.com/

CELLULOSIC FIBERS

- **Algalife** is a German-Israeli company that is growing fibers and dyes using lab-grown algae. https://www.alga-life.com/

- **Circular Systems Agraloop™ Biorefinery** converts food crop waste into high-value natural fiber products in a cost competitive and scalable way. The process also yields an organic fertilizer that can be returned to the fields. A 2018 Global Change Award winner. https://www.circular-systems.com/agraloop

- **Infinited Fiber** technology can turn textile, agricultural, and cardboard waste into new fiber. https://infinitedfiber.com/

- **Ioncell**, a Finnish-based company, has a proven technology at lab scale to convert cellulosic waste into textile fibers. It is currently at pilot phase and plans to reach proof of concept by 2021. A 2016 Global Change Award winner. https://ioncell.fi/

- **Spinnova**, another Finnish-based company, produces cellolosic fiber from wood and cellolosic waste streams without the need for first dissolving pulp. The process saves water and energy and requires no harmful chemicals. https://spinnova.com/

FERMENTATION

- Based in the U.S., **Allbirds** is a successful shoe company that produces the foam for the shoes' soles through fermentation. https://www.allbirds.com/
- **AMSilk's Biosteel**® fibers are functional silk biopolymers that can be spun to produce a variety of performance characteristics. Based in Germany, the company functions at an industrial scale. https://www.amsilk.com/industries/biosteel-fibers/
- **Faber Futures** is developing a fermentation-based dyeing method using bacteria such as Streptomyces coelicolor. https://faberfutures.com/
- **Colorifix** create's color in the lab and then ships a tiny quantity of live microorganisms to local fermentation partners who then grow the color, like beer, using by-products of the sugar production industry. The process requires no toxic chemicals, one-tenth of the water of standard processes, and allows fiber dyeing to take place at 37°C. https://colorifix.com/
- The **Hong Kong Research Institute of Textiles and Apparel Limited (HKRITA)** uses enzymes to break down food waste, followed by fermentation and polymerization to produce biodegradable PLA fibers. http://www.hkrita.com/commercial-opportunities-detail.php?id=62
- **Spiber's Brewed Protein™** fermented materials can be processed into fine filament fibers or spun yarns with a variety of performance characteristics. After 15 years of R&D, this Japanese company is now focused on scaling up for mass production. https://www.spiber.jp/en/brewedprotein/
- **Werewool** is developing a platform to design fibers at the DNA level for sustainable textiles with inherent properties such as color, moisture management, and stretch, that meet the demands of today's consumers. 2020 H&M Global Change Award Winners. https://www.werewool.bio/

GASIFICATION + FERMENTATION

- **Air Miners** is an index of companies and projects that mine carbon from the air. http://www.airminers.org/
- **Kiverdi** breaks down carbon materials into their fundamental elements and builds them back up into a range of bio-based products. Kiverdi can transform plastic or any carbon-based material into new biodegradable materials and packaging. It can also transform CO2 into sustainable protein (and thus could contribute to a reduction in the amount of arable land needed for food production). https://www.kiverdi.com/about
- **LanzaTech's** carbon recycling technology using bacteria to convert pollution from an emission source like a steel meel or landfill site into fuels and chemicals. https://www.lanzatech.com/

OTHER TRANSITION TECHNOLOGIES

- **Recycling Revolution**, a partnership between H&M and HKRITA and its team of researchers is exploring a hydrothermal approach to recycling, dubbed The Green Machine, as well as a biological method to recycle blends. https://hmfoundation.com/recycling-revolution/
- **SaXcell** is a regenerated virgin textile fiber made from chemically recycled domestic cotton waste. Sorting is currently done manually. http://saxcell.nl/
- **Worn Again Technologies** has developed a chemical polymer recycling technology that offers innovative ways of handling blended textiles. http://wornagain.co.uk/

Acknowledgements

Funder / Partner

Laudes Foundation

Special Thanks

The Biomimicry Institute would like to thank the following for sharing their time and expertise with us, primarily through interviews and occasionally via correspondence:

Cees Anton, *Director, Origame*
Laura Balmond, *Programme Manager for Make Fashion Circular, Ellen MacArthur Foundation*
Kevin Bayuk, *Senior Financial Fellow, Project Drawdown; Co-founder, LIFT Economy*
Jay Bolus, *President, McDonough Braungart Design Chemistry*
Lauren Bright, *Senior Manager, Sustainable Product Innovation at Aro, Gap, Inc.*
Caroline Brown, *Managing Director, Closed Loop Partners*
Sophie Buchel, *Consultant and Researcher, Drift for Transition*
Rebecca Burgess, *Executive Director, Fibershed; Chair of the Board, Carbon Cycle Institute*
Dr. Peter Christensen, *Chemist and circular economy expert*
Dr. Lisa Dyson, *Founder and CEO, Kiverdi*
Stacy Flynn, *CEO and founding partner, Evrnu*
Dr. Jonathan Foley, *Executive Director, Project Drawdown*
Ricardo Garay, *Agraloop Project Coordinator, Circular Systems*
Pascale Gatzen, *head, Fashion Design Masters Program, ArtEZ University of the Arts*
Annie Gullingsrud, *Chief Strategy Officer, Eon; Author, Fashion Fibers: Designing for Sustainability*
Douwe Jan Joustra, *former Head of Circular Transformation, C&A Foundation*
Sarah Kelley, *Project Director, Special Project on Sustainable Fibers and Textiles, Sustainable Agriculture and Food Systems Funders*
Sibbe Krol, *Senior Program Manager, Apparel & Electronics, IDH The Sustainable Trade Initiative*
Domenica Liebowitz, *Founder and Creative Director, Averti*
Megan McGill, *Senior Programme Manager, Laudes Foundation*
Curt McNamara, *Adjunct Faculty, Minneapolis College of Art and Design; Chair, Natural Systems Working Group, International Council on Systems Engineering*
Megan Meiklejohn, *Sustainable Materials & Transparency Manager, Eileen Fisher*
Lewis Perkins, *CEO, Apparel Impact Institute*
Amina Razvi, *Executive Director, Sustainable Apparel Coalition*
Francois Souchet, *Lead for Make Fashion Circular, Ellen MacArthur Foundation*
Kirsty Stevenson, *Senior Director for Global Sustainability, Gap, Inc.*

Special acknowledgement to the authors of this report:
Eleanor Banwell
Megan Schuknecht
Beth Rattner
Natasja Hulst
Brian Dougherty, *Celery Design*

Endnotes

1. U.S. Bureau of Labor Statistics, Consumer Price Index for All Urban Consumers: Apparel in U.S. City Average [CPIAPPSL], retrieved from FRED, Federal Reserve Bank of St. Louis; https://fred.stlouisfed.org/series/CPIAPPSL, March 7, 2020.
2. Ellen MacArthur Foundation. (2017). A new textiles economy: Redesigning fashion's future.
3. Steidinger, B.S., Crowther, T.W., Liang, J. et al. (2019). Climatic controls of decomposition drive the global biogeography of forest-tree symbioses. Nature, 569, 404–408. https://doi.org/10.1038/s41586-019-1128-0
4. Mayumi, K. (2009). Nicholas Georgescu-Roegen: His Bioeconomics Approach to Development and Change. Development and Change, 40(6), 1235-1254. https://onlinelibrary.wiley.com/doi/full/10.1111/j.1467-7660.2009.01603.x
5. England, J.L. (2013). Statistical physics of self-replication. The Journal of Chemical Physics, 139(12), 09B623_1. http://www.englandlab.com/uploads/7/8/0/3/7803054/2013jcpsrep.pdf
6. Schrodinger, E. (1944). What is life? The Physical Aspect of the Living Cell. http://www.whatislife.ie/downloads/What-is-Life.pdf
7. See https://www.quantamagazine.org/a-new-thermodynamics-theory-of-the-origin-of-life-20140122/
8. See https://www.ellenmacarthurfoundation.org/circular-economy/concept.
9. Mayumi, K. (2009) Nicholas Georgescu-Roegen: His Bioeconomics Approach to Development and Change. Development and Change, 40(6), 1235-1254.
https://onlinelibrary.wiley.com/doi/full/10.1111/j.1467-7660.2009.01603.x
10. Georgescu-Roegen, N. (1971). The entropy law and the economic process. Cambridge, Mass: Harvard University Press.
11. Georgescu-Roegen, N. (1975). Energy and economic myths. Southern economic journal, 347-381. http://www.uvm.edu/~jfarley/EEseminar/readings/energy%20myths.pdf
12. See https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8
13. See: https://www.smithsonianmag.com/science-nature/toxic-chemicals-banned-arctic-wildlife-180970209/
14. Bytingsvik, J., van Leeuwen, S., Hamers, T., Swart, K., Aars, J., Lie, E., ... & Jenssen, B. (2012). Perfluoroalkyl substances in polar bear mother–cub pairs: a comparative study based on plasma levels from 1998 and 2008. Environment International. 49, 92-99. https://www.ncbi.nlm.nih.gov/pubmed/23010253
15. Boisvert, G., Sonne, C., Rigét, F., Dietz, R. and Letcher, R. (2019). Bioaccumulation and biomagnification of perfluoroalkyl acids and precursors in East Greenland polar bears and their ringed seal prey. Environmental Pollution, 252, 1335-1343.
16. Ball, P. (2012) The unavoidable cost of computation revealed. Nature News. March 7. https://www.nature.com/news/the-unavoidable-cost-of-computation-revealed-1.10186
17. See https://www.nationalgeographic.org/media/ocean-currents-and-climate/
18. Van Der Heijden, M., Martin, F., Selosse, M., and Sanders, I. (2015). Mycorrhizal ecology and evolution: the past, the present, and the future. New Phytologist, 205(4), 1406-1423.
19. Morris, J. et al. (2019). Biology: How Life Works, 3rd edition, p. 3098.
20. See https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8
21. See http://statisticstimes.com/economy/gross-world-product.php
22. See https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8
23. See https://phys.org/news/2018-01-china-import-upends-global-recycling.html
24. See https://www.ft.com/content/360e2524-d71a-11e8-a854-33d6f82e62f8
25. Textile Exchange. (2019). Preferred Fiber & Materials Market Report 2019. https://store.textileexchange.org/product/2019-preferred-fiber-materials-report/
26. Boucher, J. and Friot, D. (2017). IUCN Primary Microplastics in the Oceans: A Global Evaluation of Sources. https:// portals.iucn.org/library/node/46622
27. The Story of Stuff Project. (2017). The Story of Microfibers. https://www.youtube.com/watch?v=BqkekY5t7KY&feature=emb_logo
28. See https://earthlogic.info/wp-content/uploads/2019/12/Earth-Logic-eversion.pdf
29. Ibid.
30. See https://fashionunited.uk/news/fashion/how-sustainable-is-recycled-polyester/2018111540000
31. See https://qz.com/india/1447653/this-indian-sportswear-brand-makes-one-t-shirt-out-of-8-pet-bottles/
32. See https://www.theguardian.com/lifeandstyle/2018/feb/19/are-we-poisoning-our-children-with-plastic
33. Ibid.
34. De Falco, F., Di Pace, E., Cocca, M. and Avella, M. (2019). The contribution of washing processes of synthetic clothes to microplastic pollution. Scientific Reports 9(1), 1-11. https://www.nature.com/articles/s41598-019-43023-x
35. Ellen MacArthur Foundation. (2017). The New Plastics Economy: Rethinking the future of plastics & catalysing action. https://www.ellenmacarthurfoundation.org/publications/the-new-plastics-economy-rethinking-the-future-of-plastics-catalysing-action
36. See https://www.nationalgeographic.com/news/2017/07/plastic-produced-recycling-waste-ocean-trash-debris-environment/
37. Geyer, R., Jambeck, J. and Lavendar Law, K. (2017). Production, Use, and Fate of All Plastics Ever Made. Science Advances 3(7). https://www.ncbi.nlm.nih.gov/pmc/articles/PMC5517107/
38. See https://app.ft.com/cms/s/360e2524-d71a-11e8-a854-33d6f82e62f8.html
39. See https://www.nationalgeographic.com/magazine/2020/03/how-a-circular-economy-could-save-the-world-feature/
40. McKeag, T. (2011) Surfing for Free: Optimizing Thermodynamic Pathways for Innovative Solutions. Proceedings: Biomimicry in Higher Education Webinar. January 29.
https://asknature.org/resource/proceedings-of-the-1st-annual-biomimicry-in-higher-education-webinar/
41. See https://www.ellenmacarthurfoundation.org/our-work/activities/new-plastics-economy/vision
42. Christensen, P.R., Scheuermann, A.M., Loeffler, K.E., and Helms, B.A. (2019). Closed-loop recycling of plastics enabled by dynamic covalent diketoenamine bonds. Nature Chemistry, 11(5), pp.442-448. https://www.nature.com/articles/s41557-019-0249-2

43. Interview with Dr. Peter Christensen, February 6, 2020.
44. See https://mcdonough.com/writings/toward-21st-century-renaissance/
45. See https://rodaleinstitute.org/why-organic/organic-basics/regenerative-organic-agriculture/
46. See http://www.regenerativeagriculturedefinition.com/
47. Meiklejohn, M. (2020). Textiles and Apparel: Fabrics Weaving A Regenerative Future. ReGen Friends panel discussion, February 27, San Francisco, CA.
48. See https://oecotextiles.wordpress.com/category/fibers/natural-fibers-2/
49. Muthu, S.S. (2018). Assessing the Environmental Impact of Textiles and the Clothing Supply Chain, 2nd Edition. Woodhead Publishing, Cambridge, MA.
50. See https://www.theguardian.com/fashion/2019/oct/01/cotton-on-the-staggering-potential-of-switching-to-organic-clothes
51. Quantis. (2018). Measuring Fashion: Insights from the Environmental Impact of the Global Apparel and Footwear Industries study.
52. Global Fashion Agenda and Boston Consulting Group. (2017). The Pulse of the Fashion Industry. Exhibit 16, 42.
53. Ibid, p. 9.
54. See https://ipbes.net/news/Media-Release-Global-Assessment
55. See an example of this in the Amsterdam Doughnut Coalition analysis: https://www.kateraworth.com/2020/04/08/amsterdam-city-doughnut/
56. Goerner S, Fiscus D, & Fath, B.D. (2015). Using energy network science (ENS) to connect resilience with the larger story of systemic health and development. Emergence: Complexity and Organization, 17 (3), 1-21.
57. Ibid.
58. See https://www.usgs.gov/center-news/biodiversity-critical-maintaining-healthy-ecosystems
59. See https://ipbes.net/news/Media-Release-Global-Assessment
60. See http://www.safsf.org/fibers/
61. See http://www.fao.org/state-of-food-agriculture/en/
62. Ditty, S. (2015). It's Time for a Fashion Revolution. Fashion Revolution.
63. Steffen, W. et al. (2015). Planetary boundaries: Guiding human development on a changing planet. Science. 347: 6223. February 13.
64. Global Fashion Agenda and Boston Consulting Group. (2017). The Pulse of the Fashion Industry. Exhibit 3, 10.
65. Duffy, J.E., Cardinale, B.J., France, K.E., McIntyre, P.B., Thébault, E., and Loreau, M. (2007) The functional role of biodiversity in ecosystems: incorporating trophic complexity. Ecology Letters, 10(6), 522-538.
66. Morris, J. et al. (2019). Biology: How Life Works, 3rd edition.
67. Ibid.
68. Duffy, J.E., Cardinale, B.J., France, K.E., McIntyre, P.B., Thébault, E., and Loreau, M. (2007) The functional role of biodiversity in ecosystems: incorporating trophic complexity. Ecology Letters, 10(6), 522-538.
69. European Union. (2010). The factory of life: Why soil biodiversity is so important.
70. Wall, D., Nielsen, U. & Six, J. (2015). Soil biodiversity and human health. Nature, 528, 69–76.
71. Hatfield, J., Sauer, T., & Cruse, R. (2017). Chapter One-Soil: The Forgotten Piece of the Water, Food, Energy Nexus in Advances in Agronomy, 143, 1-46.
72. Goerner S, Fiscus D, & Fath, B.D. (2015). Using energy network science (ENS) to connect resilience with the larger story of systemic health and development. Emergence: Complexity and Organization, 17 (3), 1-21.
73. See https://fashionista.com/2019/03/regenerative-agriculture-farming-sustainable-fashion
74. Ibid.
75. See https://d1cqrq366w3ike.cloudfront.net/http/DOCUMENT/SheepUSA/CharacteristicsOfWool.pdf
76. See https://textilelearner.blogspot.com/2012/01/linen-fiber-characteristics-of-linen.html and https://textilelearner.blogspot.com/2011/05/physical-properties-of-cotton-fiber-end_846.html
77. See https://www.stexfibers.com/about
78. See https://rodaleinstitute.org/why-organic/issues-and-priorities/carbon-sequestration/
79. See the work of Sally Fox, Foxfibre® naturally colored cotton: https://fibershed.org/2019/11/08/california-cotton-fields-sally-fox-reinvented-cotton-by-going-back-to-its-roots/
80. Ellen MacArthur Foundation. (2017). A new textiles economy: Redesigning fashion's future.
81. Global Fashion Agenda. (2020). CEO Agenda. https://globalfashionagenda.com/ceo-agenda-2020/
82. Burgess, R. with White, C. (2019). Fibershed: Growing a Movement of Farmers, Fashion Activists, and Makers for a New Textile Economy. Chelsea Green Publishing. P. 159.
83. See https://www.fastcompany.com/40448774/your-clothes-might-be-destroying-the-rainforest and https://hotbutton.canopyplanet.org/
84. See https://www.circular-systems.com/agraloop/
85. Lelieveld, J., Evans, J.S., Fnais, M., Giannadaki, D. and Pozzer, A. (2015). The contribution of outdoor air pollution sources to premature mortality on a global scale. Nature, 525(7569), 367-371. https://www.nature.com/articles/nature15371
86. See https://www.wri.org/blog/2017/04/restoration-revolution
87. See https://www.labiotech.eu/industrial/biofabrication-fashion-industry/
88. See https://www.chemistryworld.com/features/recycling-clothing-the-chemical-way/4010988.article
89. See https://cordis.europa.eu/article/id/411525-discarded-textile-now-a-raw-material-for-the-chemical-and-textile-industries
90. GreenBlue. (2017). Chemical recycling. Making fiber-to-fiber recycling a reality for polyester textiles.
91. See https://www.engineeringnz.org/news-insights/doing-things-differently-allbirds/
92. Ibid.
93. See https://www.sciencedirect.com/book/9780128168561/biofuels-alternative-feedstocks-and-conversion-processes-for-the-production-of-liquid-and-gaseous-biofuels
94. Benyus, J. (1998). Biomimicry: Innovation Inspired by Nature. New York: Quill.
95. Joustra, D. J., van Leenders, C. and Wijffels, B. (2014). Ecomimicry: Ten Perspectives from Nature. https://issuu.com/douwejanjoustra8/docs/ten_perspectives_from_nature_-_2014

96. Global Fashion Agenda and Boston Consulting Group. (2017). The Pulse of the Fashion Industry. https://globalfashionagenda.com/wp-content/uploads/2017/05/Pulse-of-the-Fashion-Industry_2017.pdf
97. Anonymous attribution at this time, but the sentiment was shared by no fewer than three major brands.
98. Interview with Rebecca Burgess, March 12, 2020.
99. Wahl, D.C. (2016). Designing Regenerative Cultures, and "The Grace of Import Replacements" https://centerforneweconomics.org/publications/the-grace-of-import-replacement/
100. See https://all3dp.com/2/3d-printed-shoes/
101. Abbott, A. and Ellison, M., eds. (2008). Biologically Inspired Textiles. Woodhead Publishing.
102. See https://centerforneweconomics.org/publications/ecological-design-reinventing-the-future/
103. See https://www.kateraworth.com/2020/04/08/amsterdam-city-doughnut/
104. See https://vimeo.com/274599205
105. See https://truthout.org/articles/reimagine-don-t-seize-the-means-of-production/
106. Existing examples include: WikiHouse, a nonprofit foundation sharing templates for modular housing; L'Atelier Paysan, an open-source cooperative fostering technological sovereignty for small- and medium-scale ecological agriculture; Farm Hack, a farmer-driven community network sharing open-source know-how amongst do-it-yourself agricultural tech innovators.
107. Burgess, R. with White, C. (2019). Fibershed: Growing a Movement of Farmers, Fashion Activists, and Makers for a New Textile Economy. Chelsea Green Publishing, 192-193.
108. Delta Institute and Farmland LP. (Valuing the Ecosystem Service Benefits from Regenerative Agriculture Practices.
109. See also the work of Dr. Gretchen Daily and the Natural Capital Project: https://ccb.stanford.edu/people/gretchen-c-daily
110. See https://dnfi.org/
111. Bhat, G. and Parikh, D.V. (2010). Biodegradable Materials for Nonwovens. Chapter 3 in Applications of Nonwovens in Textiles. Woodhead Publishing Series in Textiles.
112. See https://news.nike.com/press-release/news/coca-cola-ford-heinz-nike-and-procter-gamble-form-collaborative-to-accelerate-development-of-products-made-entirely-from-plants
113. Taylor, B. (2019). Healthy Soils To Cool the Planet: A Philanthropic Action Guide. Breakthrough Strategies Solutions. https://www.breakthroughstrategiesandsolutions.com/soilguide
114. See https://www.chemforward.org/stacy-bio
115. See https://www.roadmaptozero.com/

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