Evaluating Cotton Apparel with Dynamic Life Cycle Assessment: The Climate Benefits of Temporary Biogenic Carbon Storage

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Static life cycle assessment (LCA) methodologies fail to consider the temporal profiles of system inputs and outputs (including emission timing), such that they underestimate the benefits of temporarily stored biogenic carbon in bioproducts, such as cotton. This research focuses on greenhouse gas emission timing and applies dynamic emission accounting to the life cycle of cotton woven pants. The significance of temporary biogenic carbon storage and emission timing is illustrated by converting the 2017 Cotton Incorporated static LCA to a dynamic model using the Dynamic Carbon Footprinter (baseline scenario). A reduction in cumulative radiative forcing for dynamic relative to static modeling of 22%, 5%, and 2% are observed at 10-years, 30-years, and 100-years, respectively. Alternative scenarios analyzed include converting cotton woven pants at end of life to bioenergy, to compost, or to building insulation, an alternative cotton production scenario using regenerative agricultural practices, and two pants extended lifetime scenarios. The regenerative agricultural practice scenario provides reductions in cumulative impacts compared to the baseline scenario of 96%, 69%, and 105% after 10, 30, and 100-years, respectively. A 3x extension in the lifetime of pants provides a benefit in reduced cumulative impacts of 31%, 40%, and 41%, after 10, 30, and 100-years, respectively. This case study with cotton demonstrates that dynamic LCA is a useful tool for assessing the benefits of biobased products, and it allows for more nuanced analysis of reductions in climate impacts in both the short- and long-term time horizons.

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INTRODUCTION

Life cycle assessment (LCA) is an environmental accounting tool that has been widely used to identify hotspots and evaluate the impacts of products and services across their life cycle. The first ever published LCA was a cradle-to-gate assessment conducted by Coca-Cola in 1969 (Bauman and Tillman 2004). The original use case for the tool was centered on facility assessments. Over five decades later, LCA has been applied to a wide range of product systems including agricultural commodities and other bioproducts with much broader system boundaries and complex physical processes to model. For LCAs applied to these natural systems, the set of assumptions and methodological decisions used can dramatically influence the results. Some key methodological decisions include defining the system boundaries, functional unit selection, co-product allocation, defining the temporal scope, life cycle inventory data collection approach, and accounting for biogenic carbon uptake and emission timing.

Temporal boundary selection (*e.g.*, the timeframe used to evaluate the impacts) is critical, since society is focused on reducing our overall climate impacts in the near term. For greenhouse gas reporting, using the concept of global warming potential (GWP) at the 100-year time horizon (GWP-100) has become the standard within the scientific community. The Intergovernmental Panel on Climate Change (IPCC) developed the concept of GWP, which can be calculated for any gas (i) using Eq. 1 (Myhre *et al.* 2013a),

$$GWP_i(H) = \frac{AGWP_i(H)}{AGWP_{CO_2}(H)} = \frac{\int_0^H RF_i(t)dt}{\int_0^H RF_{CO_2}(t)dt} \tag{1}$$

where the Absolute Global Warming Potential (AGWP) of greenhouse gas (i) is given by the integral of the Radiative Forcing (RF) of a pulse emission of gas (i) at a specific point in time (*t*) relative to the integral of the RF of a 1 kg pulse emission of CO_2 at time (*t*) and is provided in Watt years per square meter per kilogram of gas (W yr m^{-2} kg^{-1}). The RF of a given gas (i) is calculated by Eq. 2 (Lan and Yao 2022),

$$RF_i = A_i C_i \tag{2}$$

where A_i is the radiative efficiency and C_i is the amount of gas left in the atmosphere after the initial pulse emission.

The early adoption of the 100-year GWP by the Kyoto Protocol cemented its use in the scientific community and by other industry stakeholders (Breidenich *et al.* 1998; Shine 2009). However, both the 100-year time horizon and the concept of GWP have sparked debate in the literature. Kleinberg (2020) argued that using GWP to evaluate climate change impacts is "unphysical, unintuitive, arbitrary, ignores the time dependence of emission sources, and is in some cases misleading". They argue that beyond a 20-year time horizon, the GWP measure becomes meaningless. Lynch *et al.* (2020) indicate the GWP-100 metric falls short in accurately representing the contrasting impacts of short- and long-lived climate pollutants, leading to ambiguities in its relationship with actual global warming. With many organizations and nations striving to reach their climate commitments by 2050, these short-term differences in individual greenhouse gas species radiative efficiency become even more important (Lynch *et al.* 2020).

A significant methodological decision in the LCA process is determining how to account for the timing of climate-changing emissions within the study. Traditional static LCAs sum the global warming impacts (GWIs) occurring over a specified timeframe, typically 100-years, and model them as if they all occur in the first year (Daystar *et al.* 2017). This static LCA approach causes inconsistent temporal boundaries, which can distort the real-world implications of the GHG emissions occurring over the chosen analytical time horizon (Levasseur *et al.* 2013; Daystar *et al.* 2017). This inconsistency ignores the actual short-term reduction in cumulative radiative forcing due to temporarily stored biogenic carbon, which is shown to be important in bioproducts products with longer lifespans (Levasseur *et al.* 2013; Daystar *et al.* 2017). Durable cotton textiles provide longer-term biogenic carbon storage as well, the benefits of which have gone unrealized under existing LCAs applying static GHG accounting approaches. Further, when applying static LCA methodologies, emissions occurring later in the time horizon (*e.g.*, landfill emissions following garment disposal after an 8-year life span) are incorrectly accounted for within a 100-year (or other) time horizon as all emissions are assumed to occur at year 1.

A more comprehensive approach to evaluating the benefits of biogenic carbon uptake, storage, and emission timing is a system known as dynamic life cycle assessment (Levasseur *et al.* 2010, 2013). This concept was originally developed by Levasseur *et al.* (2010) where dynamic characterization factors (DCF) are used to evaluate the radiative forcing impact of a GHG through time, given by Eq. 3,

$$DCF(t) = \int_{t-1}^{t} aC(t)dt \tag{3}$$

where the dynamic characterization factor at time *t* is given in Watts per year per square meter (W/yr/m^2). The instantaneous radiative forcing per unit of mass increase in the atmosphere, *a*, in Watts per square meter per kilogram (W/m^2/kg) is then multiplied by the atmospheric load over of the GHG at time *t* after the emission occurs (kg). The DCFs are then used to calculate the immediate climate impact of the greenhouse gasses considered, known as the Instantaneous Global Warming Impact (GWI_{inst}), as shown by Eq. 4:

$$GWI_{inst}(t) = \sum_{i=0}^{t}[gCO_2(i)DCF_{CO2}(t-1)] + \sum_{i=0}^{t}[gCH_4(i)DCF_{CH4}(t-1)] \tag{4}$$

In this example, the expression provides the GWI_{inst} at time *t* for carbon dioxide and methane; however, the expression would expand to match the number of GHGs being evaluated. The authors' example equation sums the products of emission factors for CO_2, $gCO_2(i)$, and CH_4, $gCH_4(i)$, with their respective DCFs: $DCF_{CO2}(t-1)$ and $DCF_{CH4}(t-1)$ from time *0* to time *t*. The dynamic GHG inventory result (the sum of the positive and negative emissions) for year *i* (in kg) is represented by the expression $gCO_2(i)$ and $gCH_4(i)$, for carbon dioxide and methane, respectively, in this example. These results are used to evaluate the cumulative impact the gasses have on the atmosphere (GWI_{cum}) over the specified time horizon by using Eq. 5,

$$GWI_{cum}(t) = \sum_{i=0}^{t} GWI_{inst}(i) \tag{5}$$

where the aggregate of all the instantaneous global warming impacts (GWI_{inst}) is analyzed for each preceding year up to the current time *t*.

While there are many life cycle assessment studies focused on textiles, the majority of these apply traditional static LCA methodologies and do not consider emission timing. Liu *et al*. 2024 evaluates the greenhouse gas emissions across the life cycle of t-shirts made from cotton, polyester, and viscose. Their research finds that yarn manufacturing and product use phases are the primary contributors to the carbon footprint due to the associated energy consumption. The study highlights the significant role of carbon sequestration in plant-derived fibers such as cotton and viscose, which become more beneficial as the product's service life increases (*e.g.*, longer carbon storage). The study recommends technological innovation in production, greater reliance on renewable energy, and encouraging consumers to prolong the life cycle of products as ways to reduce climate impacts of textile products. However, while the research alludes to the potential benefits of storing carbon in clothing such as cotton, it does not directly quantify this metric.

Biogenic carbon uptake and emission timing has been an ongoing focus of the building and forest products sectors due to their relatively long-term carbon sequestration potential compared to many other products. Hoxha *et al.* (2020) explore this concept in detail in their review of various LCA accounting methods for evaluating biogenic carbon uptake and emissions in an energy-efficient timber building. The authors compared traditional static LCA approaches against three alternative biogenic carbon accounting methods, including a carbon neutrality approach (*e.g*., the 0/0 approach), the -1/+1 approach, and a dynamic modelling approach with two scenarios: carbon uptake by the forest before extraction and carbon uptake by the forest after extraction. Results showed substantial differences in the global warming values from each method, ranging from 16% when evaluating the building as a whole and up to a 200% difference when evaluating individual building components. Overall, the study concluded that the dynamic approach provided the most reliable and understandable results of the methods evaluated.

It is important to acknowledge there are many other methods for addressing biogenic carbon uptake and emission timing in LCA such as the Lashof method, GWPbio, Müller-Wenk and Brandão, and the carbon footprint method (Brandão *et al*. 2018; Liu *et al*. 2023), which each offer unique ways to account for the temporal aspects of greenhouse gas emissions. These methods vary in their application and rely on the use of carbon dioxide equivalents, which discount the unique physical impacts of each individual GHG species as previously discussed. Using a dynamic approach better evaluates the environmental impacts of products by accounting for the timing of emissions within a consistent temporal scope (Daystar *et al.* 2017). Applying dynamic life cycle assessment methodologies to cotton textiles can allow for a better understanding of the real-world climate benefits associated with a reduction in radiative forcing over a defined period of time. Through converting the Cotton Incorporated LCA from traditional nondynamic accounting to dynamic accounting, it is shown in this work how important this reduction in radiative forcing can be, even at the garment level. This work evaluates the benefits of stored biogenic carbon in textiles at different time horizons by highlighting different levers for change across the cotton supply chain.

EXPERIMENTAL

This paper leverages existing data from Cotton Incorporated's LCA (Cotton Incorporated 2017) and applies a dynamic GHG emission timing profile to the life cycle of cotton woven pants to contrast the static emission model with various scenarios across 10, 30, and 100-year time horizons. The global cotton LCA provides full cradle to grave impacts of cotton garments (t-shirt, knit polo shirt, and casual woven pants) at each production stage including production (from seed to finished ginned bale), manufacturing (including cut and sew and transportation), consumer use (including washing, drying, ironing), and product end of life (incineration and landfilling) (Cotton Incorporated 2017; Daystar *et al.* 2019). To better understand the discrete impacts and timing of emissions across a cotton textile products' life cycle, the Dynamic Carbon Footprinter (Levasseur 2010) was utilized with a focus on woven pants. The functional unit for the cotton production phase in the Cotton Incorporated LCA is 1,000 kg of ginned cotton lint manufactured into 2,049 pairs of casual woven pants. The use phase assumes use impacts (washing, drying, duration of service, *etc.*) and end of life (EOL) impacts following approximately 4 years of use (Cotton Incorporated 2017; Daystar *et al.* 2019).

Six scenarios were established to illustrate the importance of emission timing, biogenic carbon uptake, and enhanced sustainability practices across the cotton supply chain: 1) dynamic life cycle assessment approach, 2) regenerative cotton production, 3) long term carbon storage at product end-of-life, 4) garment composting at product end-of-life, 5) combustion with energy recovery, and 6) extended product lifetime. The majority of the climate impacts in Cotton Incorporated's global cotton LCA are driven by carbon dioxide, methane, and nitrous oxide and thus are the focus of this work and the dynamic modeling approach.

Cotton Life Cycle Assessment Data Disaggregation

The first scenario takes the data from the static Cotton Incorporated LCA model (Cotton Incorporated 2017), disaggregates the data, and converts the results into a dynamic emission model. Results of the Cotton Incorporated LCA are provided in carbon dioxide equivalents, which is a common industry practice. However, this is not ideal for dynamic modeling. In dynamic LCA modeling, both the timing of emissions and the individual GHG species is important as each individual GHG species (*e.g.*, carbon dioxide, methane, nitrous oxide, *etc.*) provides varying radiative efficiencies and global warming potentials (Myhre *et al.* 2013a). In dynamic LCA modeling, understanding the timing of emissions associated with each GHG species is critical. Working with LCA experts from Cotton Incorporated, disaggregated GHG emissions from the original LCA model were exported and utilized to determine the quantity of individual emissions at each production stage. The disaggregated emission data and relative impacts at each life cycle phase is provided in Table 1. The table also provides the timing of emissions associated with each life cycle phase.

Table 1. Woven Pants Disaggregated GHG Emission Values Based on (Cotton Incorporated 2017) with Emission Timing Assumptions

Life Cycle Phase	**Emission Timing**	**GHG Species**	**IPCC Emission Factor (GWP-100)** (Myhre *et al.* 2013a)	**CI LCA Model Export (% GHG Contribution to CO_2e)**[1,2]	**CI LCA GWP Total (CO_2e)**[3]	**Calculated GHGs Values from CI LCA (kg of Gas Species)**[4]
Production (Seed to Bale)[5]	1 Year	CO_2	1	65.1%	-113	-595.5
		N_2O	265	27.0%		1.5
		CH_4	28	7.9%		3.3
Manufacturing, Cut and Sew, and Transportation	1 Year	CO_2	1	91.8%	11489	10546.9
		N_2O	265	0.5%		0.2
		CH_4	28	7.7%		31.6
Use Phase	4 Years	CO_2	1	85.2%	8160	6952.3
		N_2O	265	0%		0
		CH_4	28	14.8%		43.1

End of Life (Incineration)	2 Years	CO_2	1	60.5%	740	447.6
		N_2O	265	0.1%		0.002
		CH_4	28	39.5%		10.4
End of Life (Landfill)		CO_2 [6]	1	60.6%	758	459.4
		CO_2 (carbon sequestration factor)[7,8]	1	-		-34.4
		N_2O	265	0.1%		0.002
		CH_4	28	39.3%		10.6
End of Life (Litter)		CO_2	1	60.6%	122	73.7
		N_2O	265	0.1%		0.0003
		CH_4	28	39.3%		1.7

Notes:

1: Individual GHG species data were exported from LCA for Experts (*fka.*, GaBi) model to obtain individual GHG quantities per production phase and were used as the basis for determining percent contributions for individual GHGs.

2: Individual GHG species were converted back to CO_2e using appropriate emission factors and compared as a percentage of the total CO_2e emissions for each production phase step to obtain % GHG contribution values.

3: From Cotton Incorporated 2017 Global Cotton LCA (CI LCA)

4: Published CO_2e values per production phase in Cotton Incorporated 2017 LCA were used to back calculate individual (GHG mass by taking % GHG contribution to CO_2e × Published LCA GWP CO_2e) / IPCC Emission Factors. Emission factors from Myhre *et al.* (2013a).

5: Production (Seed to Bale) calculated GHG value for CO_2 incorporates a biogenic carbon credit of 1540 kg CO_2e as published from CI LCA (Cotton Incorporated 2017). This credit includes biogenic carbon uptake at the field level from plant growth shown as Field Emissions of -982 kg CO_2 eq. Without the carbon credit, Field Emission values would be positive and higher with 558 kg CO2 eq mostly from fertilizer field emissions of N_2O.

6: Assume a 2 year degradation based on office paper decay rate from Wang *et al.* (2015).

7: Assume 0.02 g/g carbon sequestration factor based on office paper decay rate from (Wang *et al.* 2015).

8: Calculation for sequestration: 468 kg garment × 0.02 kg C/kg material sequestration in landfill × 3.67 (kg C conversion factor to CO_2e) = 34.35 kg CO_2 permanently sequestered

Assumptions were made from each production stage listed in Table 1 to provide the duration of storage and emission timing associated with each stage. Those data provided the foundation for the dynamic LCA model used as the baseline to compare subsequent modeling scenarios.

Static and Dynamic LCA Modeling Approach

Static and dynamic GHG inventories with manufacturing and use phase emissions

The dynamic greenhouse gas inventory for both the dynamic and static LCA is provided in Table 2. In the dynamic LCA inventory, Year 1 emissions are associated with cotton production. Because cotton production naturally sequesters carbon from the atmosphere *via* the process of photosynthesis, a negative emission is reported. Year 2 includes the impacts associated with woven pants manufacturing, including cutting, sewing, and transportation from the gin to manufacturing facility and ultimate point of sale. Years 3 through 6 include use phase impacts including washing, drying, ironing, *etc.* for the assumed use duration of four years (Cotton Incorporated 2017; Daystar *et al.* 2019).

Year 7 includes the first year of end-of-life impacts associated with landfill, incineration, and litter impacts. Year 8 includes the second and final year of impacts associated with typical end of life pathways. Garment end-of-life impacts were based on the 2017 CI LCA, which estimated 45.7% of garments were incinerated, 46.8% went sent the landfill, and 7.5% were littered or entered a "wild landfill" situation (Cotton Incorporated 2017).

Table 2. Dynamic and Static LCA GHG Emission Inventory

Scenario Name	GHG Species	Year, Phase, and Emission (kg)							
		1P	**2M**	**3U**	**4U**	**5U**	**6U**	**7E1-1**	**8E2-1**
Dynamic LCA (with M&U[1])	CO_2	-596	10547	1738	1738	1738	1738	697	249
	CH_4	3.3	31.6	10.8	10.8	10.8	10.8	16.6	6.2
	N_2O	1.5	0.2	0	0	0	0	0.001	0.001
Dynamic LCA (without M&U[2])	CO_2	-596	-	-	-	-	-	697	249
	CH_4	3.3	-	-	-	-	-	17	6
	N_2O	1.5	-	-	-	-	-	0.001	0.001
Static LCA[3] (with M&U[1])	CO_2	17850	-	-	-	-	-	-	-
	CH_4	100.8	-	-	-	-	-	-	-
	N_2O	1.7	-	-	-	-	-	-	-
Static LCA[3] (without M&U[2])	CO_2	351	-	-	-	-	-	-	-
	CH_4	26.1	-	-	-	-	-	-	-
	N_2O	1.5	-	-	-	-	-	-	-

Notes:

1: Manufacturing and use (M&U) phase impacts included

2: Manufacturing and use (M&U) phase impacts excluded

3: Year 1 for static LCA - inventory assumes all emissions occur during the first year of the product's life cycle.

1P: Year 1 - cotton production (planting, harvesting, *etc.*) to the gin gate

2M: Year 2 - textile manufacturing including cut and sew and transportation (from gin to point of sale)

3U to 6U: Year 3 to Year 6 - use phase impacts per year for 2,049 casual woven pants

7E1-1: Year 7 - first year of product end of life including incineration, landfilling, and littering with a duration of two years. Dynamic inventory assumes all incineration takes place in the first year of end of life (457 kg of casual woven pants incinerated). Landfilling impacts for 468 kg of casual woven pants assume a 2-year decomposition, with 50% of the impacts occurring in the first year of end of life and a 2% permanent sequestration. Litter impacts for 75 kg of casual woven pants includes 50% of impacts occurring in the first year of end of life.

8E1-2: Year 8 - second year of product end of life impacts including remaining emissions from landfilling and litter. This includes the second year of landfill emissions for the 468 kg of woven pants and the second year of litter emissions for the 75 kg of woven pants.

Static and dynamic GHG inventories without manufacturing and use phase emissions

To better illustrate the benefits of temporarily storing biogenic carbon in cotton products, an alternative baseline scenario was created that removes the manufacturing and use phase emissions from the inventory. Because all textile products have manufacturing and use phase impacts, which are assumed to be similar – these emissions have been removed from selected scenario analysis. This allows for a clearer demonstration of how the temporarily stored biogenic carbon affects the overall reduction of radiative forcing. Manufacturing and use phase impacts are important but fall outside the scope of focus for the current work. Additionally, manufacturing and use phase impacts span across all fiber types, whereas biogenic carbon storage is a unique element of natural fibers, such as cotton. Table 2 also provides the greenhouse gas emission inventories for the baseline scenarios without manufacturing and use phase impacts included. The numbers and associated letters in the following summary tables indicate the year and life cycle stage (*e.g.*, 1P, 2M, 3U, *etc.*) and are defined in more detail in the notes section of Tables 2, 3, and 4.

Scenario Modelling

This section outlines the scenarios considered in the current work. These scenarios provide optimistic pathways that illustrate the climate change benefits associated with aspects of regenerative cotton production, alternative end of life scenarios for woven pants, textile recycling, improved product lifespan, and textile to bioenergy pathways. As previously mentioned, manufacturing and use phase emissions have been removed from the following scenario analysis to allow for a clearer understanding of the benefits of biogenic carbon uptake in each scenario. A summary of GHG emissions associated with each scenario is provided in Table 3.

Table 3. GHG Emission Inventories for Alternative Production and End of Life Scenarios

Scenario Name	GHG Species	Year, Phase, and Emission (kg)							
		1P	2M	3U	4U	5U	6U	7E1-1	8E1-2
Dynamic LCA (Baseline)	CO_2	-596	-	-	-	-	-	697	249
	CH_4	3.3	-	-	-	-	-	17	6
	N_2O	1.5	-	-	-	-	-	0.001	0.001
Regenerative Cotton	CO_2	-1957.3	-	-	-	-	-	697	249
	CH_4	3.3	-	-	-	-	-	17	6
	N_2O	0.7	-	-	-	-	-	0.001	0.001
Long Term Sequestration (Cotton-based Building Insulation)	CO_2	-596	-	-	-	-	-	-49.3	0
	CH_4	3.3	-	-	-	-	-	0.0002	0
	N_2O	1.5	-	-	-	-	-	0.003	0
Composting at EOL	CO_2	-596	-	-	-	-	-	171	0
	CH_4	3.3	-	-	-	-	-	2	0
	N_2O	1.5	-	-	-	-	-	0.05	0

Scenario Name	GHG Species	Year, Phase, and Emission (kg)							
		1P	2M	3U	4U	5U	6U	7E1-1	8E1-2
Combustion with Energy Recovery	CO_2	-596	-	-	-	-	-	1078	0
	CH_4	3.3	-	-	-	-	-	-0.01	0
	N_2O	1.5	-	-	-	-	-	-0.01	0

Notes:

1P: Year 1 - cotton production (planting, harvesting, *etc.*) to the gin gate

2M: Year 2 - impacts excluded from textile manufacturing including cut and sew and transportation (from gin to point of sale)

3U to 6U: Year 3 to Year 6 - impacts excluded from use phase for 2,049 casual woven pants

7E1-1: Year 7 - first year of product end of life including incineration, landfilling, and littering with a duration of two years. Dynamic inventory assumes that all incineration takes place in the first year of end of life (457 kg of casual woven pants incinerated). Landfilling impacts for 468 kg of casual woven pants assume a 2-year decomposition, with 50% of the impacts occurring in the first year of end of life and a 2% permanent sequestration. Litter impacts for 75 kg of casual woven pants includes 50% of impacts occurring in the first year of end of life.

8E1-2: Year 8 - second year of product end of life impacts including remaining emissions from landfilling and litter. This includes the second year of landfill emissions for the 468 kg of woven pants and the second year of litter emissions for the 75 kg of woven pants.

Regenerative cotton production (Climate Smart Cotton)

This scenario examines the garment level implications of the U.S. Climate Smart Cotton Program, which encourages the adoption of regenerative agricultural practices, such as cover cropping, nutrient management, and no-till farming, in cotton production. This scenario assumes that all cotton being produced for the associated 2,049 casual woven pants from Cotton Incorporated (2017) fully adopted these regenerative agricultural practices. Emission reduction assumptions for the practices were based off the project narrative from the U.S. Climate Smart Cotton Program proposal (U.S. Cotton Trust Protocol 2023). The project narrative estimates a reduction of 0.32 metric tons (MT) of CO_2 equivalents (CO_2e) for the adoption of cover cropping, 0.19 MT CO_2e reduction for no-till adoption, and 0.08 MT CO_2e for nutrient management. To translate these benefits to the same functional unit evaluated in this study, a weighted average yield of 824 lb cotton lint per acre was calculated from the Cotton Incorporated LCA. Based on the weighted average yield from that study, 2.7 acres were required to produce 1000 kg of fiber. When these practice changes are applied to 2.7 acres, the result is a 0.8 kg reduction of N_2O emissions from nutrient management, 507 kg of CO_2 emissions from no-till, and an 854 kg reduction of CO_2 emissions from cover cropping. In the dynamic LCA inventory for this scenario it was assumed that emission reductions for nutrient management were from reduced N_2O emissions. Cover cropping and no-till adoption were assumed to reduce CO_2 emissions.

Long term sequestration via recycled cotton-based building insulation

This scenario assumes that all the cotton woven pants are recycled into a cotton-based insulation material at their end of life. It is assumed that this insulation is used to insulate new construction residential homes, providing long term biogenic carbon sequestration. To calculate the emissions associated with the cotton-based insulation manufacturing, a screening level life cycle inventory was completed and modeled off a commercial recycling facility in Arizona. From this data, 1000 kg of woven pants are converted to 778 kg of cotton-based insulation while producing emissions of 884 kg CO_2 and less than 0.005 kg of N_2O and CH_4. Conversely, to generate the same level of insulation provided by the cotton-based insulation, 453 kg of fiberglass insulation would be required, generating 933 kg CO_2. A credit was taken under this scenario where the cotton-based insulation displaces the production of fiberglass, thus providing a negative 49 kg CO_2 benefit. Petroleum-based fibers (*i.e.*, polyethylene) used as binders in traditional fiberglass do not contain biogenic carbon and thus do not provide any net removals or storage of carbon from the atmosphere. Any emissions taking place with building end of life are assumed to occur after the 100-year timeframe considered in the study. Thus, the end-of-life emissions typically encountered in the baseline scenario are avoided under this alternative scenario.

Garment composting at product end-of-life

In this scenario, end-of-life emission impacts are reduced by composting the waste cotton textiles. Emission reductions for composting cotton textiles in this scenario are based on emission factors provided by Nordahl *et al.* (2023) for wet yard waste. For simplicity, the authors assume cotton woven pants will have similar compost emission profiles to wet yard waste and would offset that feedstock to provide a similar carbon to nitrogen (C:N) ratio in the resulting compost recipe. Emission factors from Nordahl *et al.* (2023) used are as follows: methane (CH_4) at 2.06E-03 kg/kg, nitrous oxide (N_2O) at 4.54E-05 kg/kg, and carbon dioxide (CO_2) at 1.71E-01 kg/kg. The 2,049 woven pants in the Cotton Incorporated LCA are all assumed to be diverted from typical end of life scenarios to the composting environment, resulting in a reduction in end-of-life emissions.

Combustion with energy recovery at product end-of-life

This scenario uses model results from Aspen, in which waste cotton (assumed to be pure cellulose) is burned for bioenergy production. The values generated for bioenergy in this scenario are utilized to offset the average grid emission values in the United States provided by the US Environmental Protection Agency (US EPA) in their "Emission Factors for Greenhouse Gas Inventories" summary document (US EPA 2014). US EPA eGRID data indicates the US average grid energy is 79% non-renewables and 21% renewables (including 1.2% bioenergy). The results from the Aspen model show that the combustion of one ton of cotton biomass for bioenergy production results in the emission of approximately 1,620 kg CO_2. Concurrently, this process generates about 0.97 Megawatt-hours (MWh) of energy. In this scenario the conventional end-of-life emissions are replaced by the positive emissions of 1,620 kg CO_2 minus the grid emission factor credit of 542 kg CO_2 associated with the production of the 0.97 MWh created by cotton bioenergy. Negative emission values of 0.01 kg of methane and nitrous oxide are taken as an avoided emission from typical US average grid energy production. These credits are used in the end-of-life emission reductions associated with the benefits of this scenario.

Table 4. GHG Emission Inventories for Extended Lifetime Scenarios (Including Manufacturing and Use Phase Emissions)

Scenario Name	GHG Species	Year and Emission (kg)															
		1	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16
Two cycles of typical product use (Baseline for comparing 2x lifetime)	**Production Phase**	**P1**	**M1**	**U1**	**U1**	**P2+U1**	**M2+U1**	**E1-1+U2**	**E1-2+U2**	**U2**	**U2**	**E2-1**	**E2-2**	**-**	**-**	**-**	**-**
	CO_2	-596	10547	1738	1738	1143	12285	2435	1987	1738	1738	697	249	-	-	-	-
	CH_4	3	32	11	11	14	42	27	17	11	11	17	6	-	-	-	-
	N_2O	1	0.2	0	0	1	0.2	0.001	0.001	0	0	0.001	0.001	-	-	-	-
Extended Product Lifetime 2x	**Production Phase**	**P1**	**M1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**E1-1**	**E1-2**	**-**	**-**	**-**	**-**
	CO_2	-596	1738	1738	1738	1738	1738	1738	1738	1738	1738	697	249	-	-	-	-
	CH_4	3	11	11	11	11	11	11	11	11	11	17	6	-	-	-	-
	N_2O	1	0	0	0	0	0	0	0	0	0	0.001	0.001	-	-	-	-
Three cycles of typical product use (Baseline for comparing 3x lifetime)	**Production Phase**	**P1**	**M1**	**U1**	**U1**	**P2+U1**	**M2+U1**	**E1-1+U2**	**E1-2+U2**	**P3+U2**	**M3+U2**	**U3+E2-1**	**U3+E2-2**	**U3**	**U3**	**E3-1**	**E3-2**
	CO_2	-596	10547	1738	1738	1143	12285	2435	1987	1143	12285	2435	1987	1738	1738	697	249
	CH_4	3	32	11	11	14	42	27	17	14	42	27	17	11	11	17	6
	N_2O	1	0.2	0	0	1	0.2	0	0	1	0.2	0	0	0	0	0	0
Extended Product Lifetime 3x	**Production Phase**	**P1**	**M1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**U1**	**E1-1**	**E1-2**
	CO_2	-596	10547	1738	1738	1738	1738	1738	1738	1738	1738	1738	1738	1738	1738	697	249
	CH_4	3	32	11	11	11	11	11	11	11	11	11	11	11	11	17	6
	N_2O	1	0.2	0	0	0	0	0	0	0	0	0	0	0	0	0.001	0.001

Notes: Production phase descriptors (*e.g.*, P1, M1, P2) describe the production phase and associated production, manufacturing, or use cycle number. For example, P1 = cotton production phase for the first product cycle, whereas P2 = cotton production phase for the second product cycle.

1: Production phase letters indicate the phase along the product life cycle (P = Production, M = Manufacturing [including transportation], U = Use, E = End of life)

2: Production phase numbers indicate the product life cycle number (*e.g.*, U1 = first garment use phase, U2 = second garment use phase, M3 = third garment manufacturing phase)
3: In certain years, two production phases may occur simultaneously and are indicated with a plus sign (*e.g.*, P2+U1 = production for the second garment with use phase for first garment)
E1-1: First year of first garment end of life impacts.
E1-2: Second year of first garment end of life impacts.
E2-1: First year of second garment end of life impacts.
E2-2: Second year of second garment end of life impacts.
E3-1: First year of third garment end of life impacts.
E3-2: Second year of third garment end of life impacts.

Increased product longevity (manufacturing and use phase impacts included)

For increased longevity scenarios, manufacturing impacts are included for context, with comparison made to the business-as-usual scenario, where new garments are manufactured after the original product reaches its end of life after 4 years. In extended use scenarios, manufacturing and use phase impacts are a key point of difference between the two product systems

This scenario evaluates this immediate action that consumers could take which avoids new product manufacturing impacts by keeping existing garments in use for longer times. This scenario also provides insights to textile manufacturers, highlighting the climate benefits of making more durable garments (*i.e.*, ones that last longer). However, technical aspects related to increasing a garments' durability are not specifically included. Additionally, the recycling of textiles is not considered in this scenario.

Increased product longevity scenarios consider the effects of extending the product lifetime by a factor of 2x and 3x, resulting in 12-year and 16-year product lifetimes, respectively. Alternatively, two and three cycles of new garment production, original use duration, and disposal are included as a point of comparison for extended lifetime scenarios. Dynamic GHG inventories for the extended lifetime scenarios are provided in Table 4. Extended product longevity scenarios alter the functional unit of one product lifetime; therefore, each product lifetime extension scenario also includes a functionally equivalent baseline for comparison (two and three cycles of typical product usage).

RESULTS AND DISCUSSION

The results of the Dynamic Carbon Footprinter are provided as the cumulative radiative forcing (GWI_{cum}) measured in Watts per year per square meter (W/yr/m^2), as shown in Eq. 5. This measure represents the total additional radiative forcing caused by each life cycle greenhouse gas emission from the start of a scenario to any specific time (t). This measure is useful in comparing different scenarios to determine which one has a more significant impact on radiative forcing over any given time horizon. Figures 1 to 4 in the subsequent sections below present the cumulative impacts within the 100-year time horizon for each scenario, with a specific focus at 10, 30, and 100 years. Tables 5 to 8 show individual cumulative impacts for each scenario at 10, 30, and 100 years.

Static and Dynamic LCA Results (With Manufacturing and Use Phase Impacts)

The results from the dynamic LCA model, which reflects the true timing of emissions during the production, manufacturing, use, and end-of-life phases of the casual woven pants, show a 22%, 5%, and 2% reduction in cumulative radiative forcing after 10, 30, and 100-years, respectively, compared to the static model (Fig. 1). This result is due to the sequestration of CO_2 during the cotton production phase, which is stored in the garment throughout its life cycle. At the garment end-of-life, biogenic carbon is emitted back into the atmosphere at year 7 and 8. This temporary biogenic carbon storage provides a net cooling effect that is not illustrated in the static LCA model and is more dramatic in earlier time horizons due to this delayed emission occurring over a larger portion of the time horizon. Figure 1 provides the cumulative radiative forcing from 0 to 100 years for both the static and dynamic models along with the key production phases (shown in red) and difference in results (shown in green) when comparing the static to the dynamic model.

Table 5 provides the cumulative radiative forcing and percent change when comparing the dynamic model to the static model.

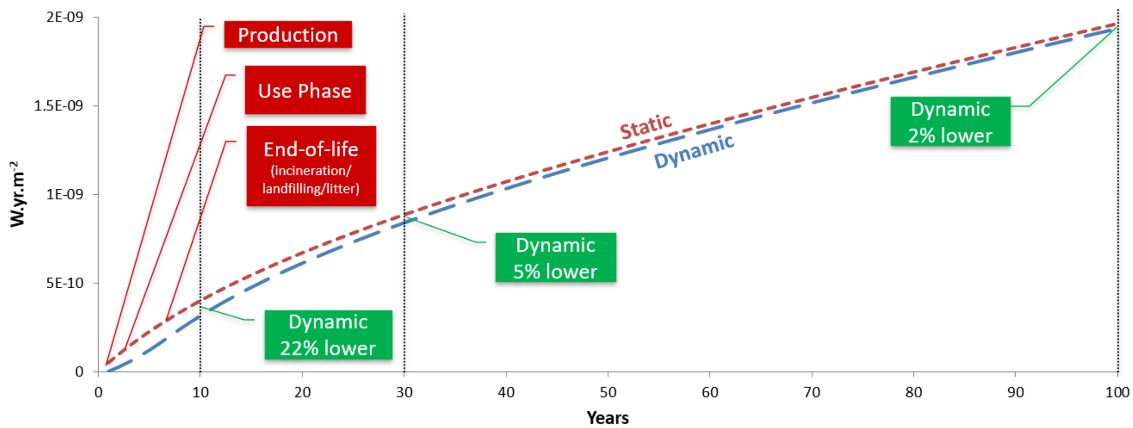

Fig. 1. Cumulative radiative forcing from 0 to 100 years for the static and dynamic models. Red callout boxes indicate the key production phases occurring during the garment's life cycle. Green callout boxes provide the percent change in results when comparing the dynamic and the static LCA models. Results include manufacturing and use phase and impacts.

Table 5. Cumulative Radiative Forcing at 10-Years, 30-Years, and 100-Years for the Static and Dynamic Models (With Manufacturing and Use Impacts)

Scenario Name	**Time Horizon**	**Cumulative Impact**	**Percent Change (Dynamic *vs.* Static)**
		W/m² yr	
Static LCA	10 Years	4.0E-10	-
	30 Years	8.9E-10	-
	100 Years	2.0E-09	-
Dynamic LCA	10 Years	3.1E-10	-22%
	30 Years	8.4E-10	-5%
	100 Years	1.9E-09	-2%

Static and Dynamic LCA Results (Without Manufacturing and Use Phase Impacts)

Unlike the previous model results shown in Fig. 1, the results in Fig. 2 are provided without including the garment's manufacturing and use phase impacts. This allows the effects of biogenic carbon storage to be highlighted. Because all fiber types (cotton, viscose, polyester, *etc*.) have a manufacturing and use phase, including those impacts in the model would mask the unique ability of natural fibers, in this case cotton, to sequester carbon. In removing those impacts from the model, the benefits of temporarily storing carbon in the garments become more apparent in terms of the reduced cumulative radiative forcing on the atmosphere. This effect is highlighted in Fig. 2, where the dynamic model clearly shows the sequestered carbon provides a near zero cumulative radiative forcing from production to product end-of-life. The static model results reflect the methodological choice that all the emissions occur during the first year, which is not reflective of reality, especially in bioproducts where biogenic carbon is stored for longer than 1 year (Levasseur *et al.* 2013; Daystar *et al.* 2017; Head *et al.* 2019), such as woven pants. Table 6 provides the cumulative radiative forcing and percent change when comparing the dynamic model to the static model. When comparing the dynamic to static results, a 53%, 11%, and 3% reduction in cumulative radiative forcing after 10, 30, and 100-years, respectively, is observed. Overall, the results indicate that, especially for short time frames, dynamic GHG accounting provides a more reasonable depiction of climate impacts, as it considers the radiative forcing provided by each individual GHG on a yearly basis.

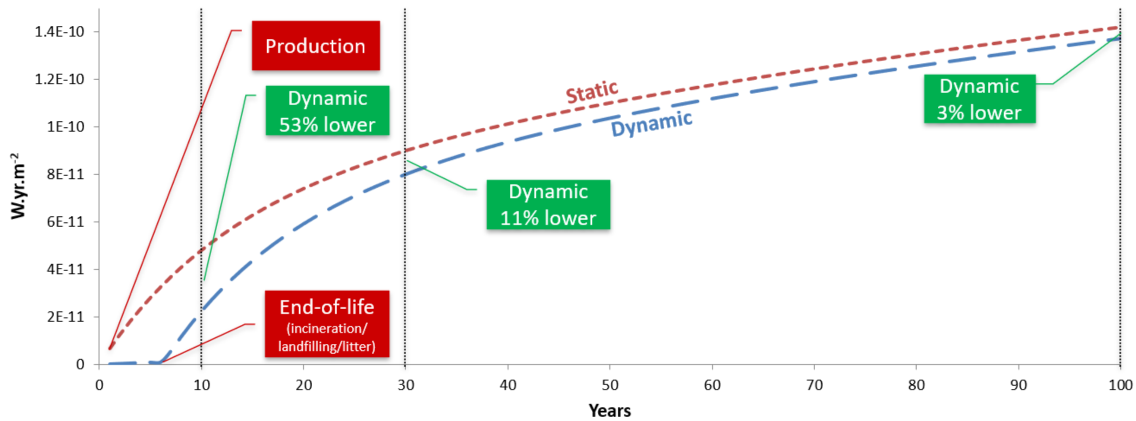

Fig. 2. Cumulative radiative forcing from 0 to 100 years for the static and dynamic models. Red callout boxes indicate the key production phases occurring during the garment's life cycle. Green callout boxes provide the percent change in results when comparing the dynamic and the static LCA models. Results do not include manufacturing and use phase and impacts.

Table 6. Static *vs.* Dynamic Results (Without Use and Manufacturing Impacts)

Scenario Name	**Time Horizon**	**Cumulative Impact**	**Percent Change (Dynamic *vs.* Static)**
		W/m^2 yr	
Static LCA	10 Years	4.8E-11	-
	30 Years	9.0E-11	-
	100 Years	1.4E-10	-
Dynamic LCA	10 Years	2.3E-11	-53%
	30 Years	8.0E-11	-11%
	100 Years	1.4E-10	-3%

Alternative scenarios versus dynamic baseline (without manufacturing and use phase impacts)

Several alternative scenarios were explored, including realistic examples that could either sequester additional carbon during cotton production or alter the release of captured carbon at the end of life, Fig. 3. The specific details of each of the scenarios are described in the Experimental section. The following section and results are provided without manufacturing and use phase impacts included, which, as previously discussed, provides a more fundamental understanding of how the stored biogenic carbon is affecting the results.

The long-term sequestration with recycled cotton-based building insulation scenario provides the overall greatest level of reduced cumulative radiative forcing of those considered in this work. Since the woven pants in this scenario are converted to home insulation after their end of life and displace the emissions associated with fiberglass manufacturing, a credit provides both long-term storage and net climate impact reductions. It is important to note that the emissions related to home demolition and disposal at the building's end of life will still occur (after year 100); however, prior to that, cumulative radiative forcing is consistently declining from years 12 to 100. This provides a net cooling effect (indicated by negative cumulative radiative forcing in Fig. 3) to the atmosphere up until the home is demolished and insulation would be discarded at end of life. Overall, the recycled cotton-based building insulation scenario provides a 94%, 100%, and 110% reduction in cumulative radiative forcing after 10, 30, and 100-years, respectively, compared to baseline conditions.

The Climate Smart Cotton scenario provides the second greatest levels of reductions in cumulative radiative forcing compared to dynamic baseline conditions. This is due to the reduced greenhouse gas emissions during cotton production in Year 1 from climate smart cotton production practices being implemented (cover cropping and no-till management practices). Additionally, Climate Smart Cotton production reduces Year 1 N_2O emissions due to reduced fertilizer utilization resulting from adopting nutrient management plans. The no-till management and cover cropping provide greater reductions in CO_2 emission in Year 1, and the nutrient management reduces N_2O emissions by half compared to baseline conditions. The results show a net cooling effect on the atmosphere (indicated by a negative cumulative radiative forcing in Fig. 3) until the garment reaches its typical end of life pathway. The increase in radiative forcing shown after year 8 is from the typical end of life pathways of the garment (incineration, landfilling, and litter). However, the reductions in CO_2 emissions occurring in Year 1 are greater than the subsequent CO_2 emissions in Years 7 and 8. The warming effects from the low levels of CH_4 and N_2O emissions occurring after product end of life cause a pulse emission to occur; however, the cumulative radiative forcing starts to decline after year 29. Overall, the Climate Smart Cotton scenario provides a 96%, 69%, and 105% reduction in cumulative radiative forcing after 10, 30, and 100-years, respectively, compared to baseline conditions.

Composting cotton garments at their end of life provides the third greatest benefit in terms of reduced cumulative forcing compared to baseline conditions. In this scenario, the emissions related to typical garment end of life (landfill, incineration, and litter) are avoided due to the assumption that all the pants enter a composting waste stream instead. Emissions related to composting are still included; however, those are reduced compared to the baseline scenario. Specifically, CO_2 and CH_4 emissions related to composting cotton garments are 82% and 91% less than the baseline scenario. However, N_2O emissions are increased 25% in the composting scenario compared to baseline conditions. Overall, the composting scenario provides a 69%, 84%, and 90% reduction in cumulative radiative forcing after 10, 30, and 100-years, respectively, compared to baseline conditions.

Of the scenarios considered, combustion of garments at end of life with energy recovery provides the least levels of reductions in cumulative radiative forcing compared to baseline conditions. The scenario diverts waste in the current end of life pathways to a bioenergy facility capable of producing energy from the waste garments. The scenario still provides a substantial reduction in cumulative radiative forcing with 63%, 60%, and 39% reductions after 10, 30, and 100-years, respectively.

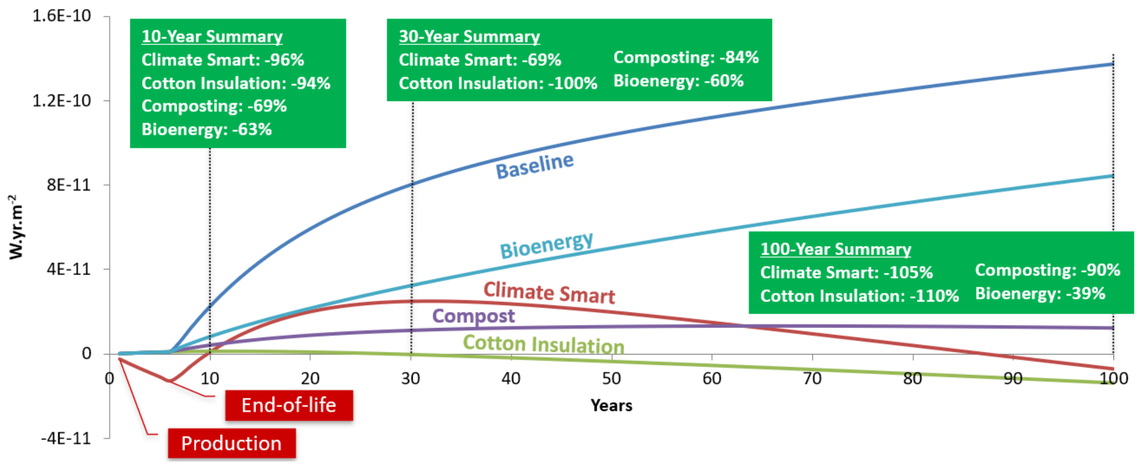

Fig. 3. Cumulative radiative forcing for dynamic baseline conditions compared to alternative scenarios for cotton production and garment end-of-life pathways (without use and manufacturing impacts). Red callout boxes indicate the key production phases occurring during the garment's life cycle. Green summary boxes provide the percent change in results when comparing the alternative scenarios to the baseline. Results do not include manufacturing and use phase impacts.

Table 7. Cumulative Radiative Forcing for Alternative Scenarios Compared to Dynamic Baseline Conditions (Without Use and Manufacturing Impacts)

Scenario Name	Time Horizon	Cumulative Impact W/m^2 yr	Percent Change Compared to Baseline
Dynamic LCA (Baseline)	10 Years	2.3E-11	-
	30 Years	8.0E-11	-
	100 Years	1.4E-10	-
Climate Smart Cotton	10 Years	-1.7E-12	-96%
	30 Years	1.8E-11	-69%
	100 Years	-2.5E-11	-105%
Long Term Sequestration (Cotton-Based Building Insulation)	10 Years	1.6E-12	-94%
	30 Years	1.2E-12	-100%
	100 Years	-9.5E-12	-110%
Composting at EOL	10 Years	7.1E-12	-69%
	30 Years	1.3E-11	-84%
	100 Years	1.3E-11	-90%
Incineration with Energy Recovery at EOL	10 Years	8.2E-12	-63%
	30 Years	3.2E-11	-60%
	100 Years	8.4E-11	-39%

Increased product longevity (with manufacturing and use phase impacts)

Increased product longevity scenarios are included to evaluate the benefits of a single pants user keeping clothing in use for longer periods of time compared to the alternative of making new garments at the typical end of life scenario. The implications of keeping a product in use for two times and three times their typical life span, 8 and 12 years, respectively, is explored. Since the main driver of impacts in this scenario is product manufacturing and use, those impacts are included to better illustrate the benefits. These scenarios assume that consumer consumption of new clothing would be reduced, and existing garments would fulfill the same purpose during the extended use duration.

Figure 4A shows that keeping a pair of pants in use for 8 years as opposed to manufacturing a new set of garments after the typical end of life every 4 years of use provides a 28%, 30%, and 30% reduction in cumulative radiative forcing at 10, 30, and 100-years, respectively. In the baseline scenario, where 2 cycles of typical use are included, two production, manufacturing, and use phase impacts are needed, which drive the increased radiative forcing under this scenario.

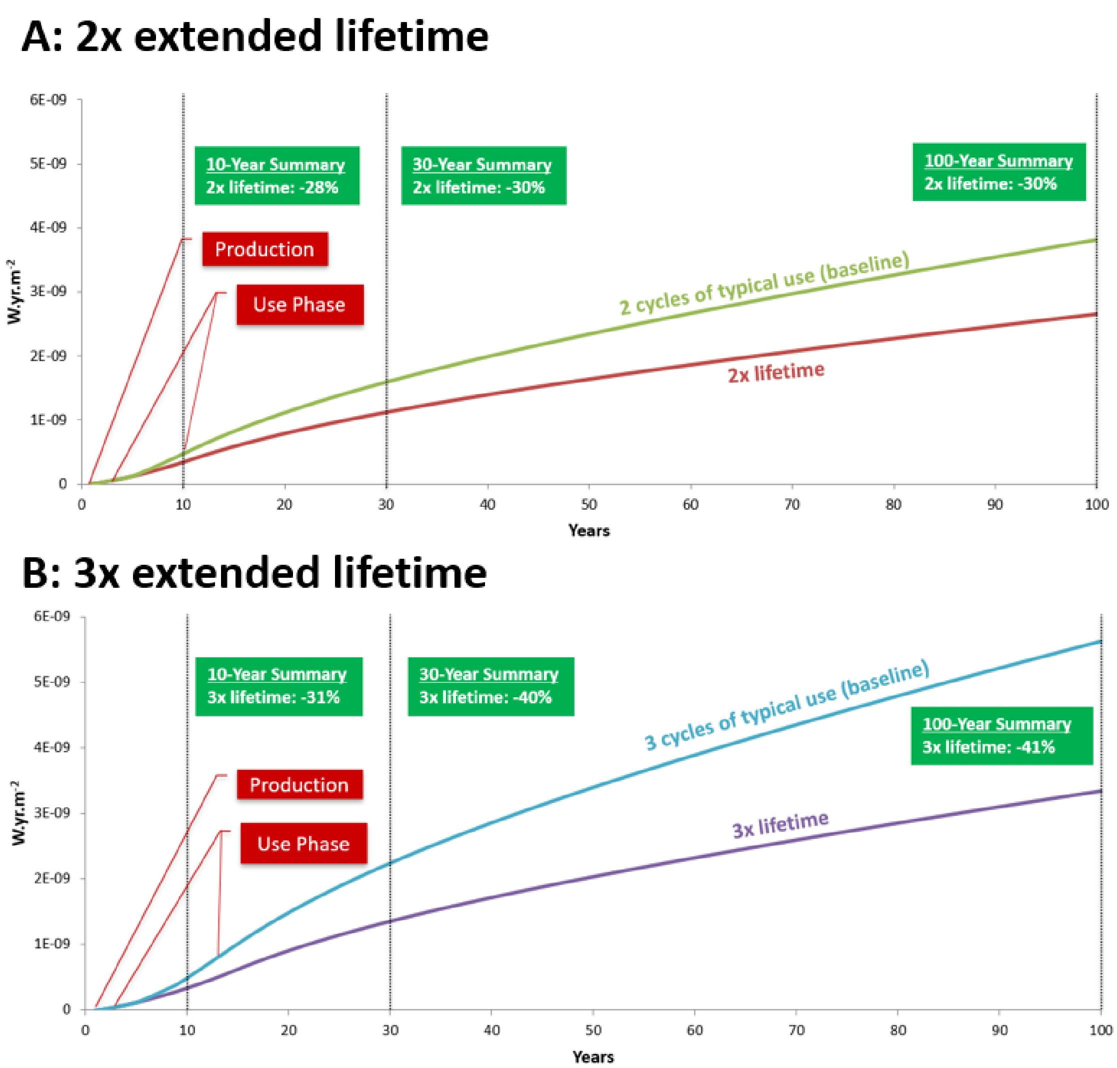

Fig. 4. A: Cumulative radiative forcing of 2x extended product lifetime scenario *versus* baseline conditions (2 cycles of typical use). B: Cumulative radiative forcing of 3x extended product lifetime scenario *versus* baseline conditions (2 cycles of typical use). Red callout boxes indicate the key production phases occurring during the garment's life cycle. Green summary boxes provide the percent change in results when comparing the extended lifetime scenarios to the baseline. Results include manufacturing and use phase and impacts.

Figure 4B shows that keeping a pair of pants in use for 12 years as opposed to manufacturing two new sets of garments after the typical end of life every 4 years of use provides a 31%, 40%, and 41% reduction in cumulative radiative forcing at 10, 30, and 100-years, respectively. In the baseline scenario, where 3 cycles of typical use are included, three production, manufacturing, and use phase impacts are needed, which drive the increased radiative forcing under this scenario. The magnitude of benefit for the 3x lifetime is greater than the 2x extended lifetime due to the increase in impacts from the third set of production, manufacturing, and use phase impacts needed in this scenario. A summary of all the baseline and extended lifetime results are provided in Table 8.

In summary, using dynamic GHG accounting and dynamic LCA provides quantitative measures of how temporarily storing carbon can help achieve short and long term climate change goals and may be beneficial in future policymaking decisions. Dynamic LCA is a useful tool for assessing the benefits of biobased products and allows for more nuanced analysis of reductions in climate impacts in both the short- and long-term time horizons.

Table 8. Cumulative Radiative Forcing Summary for Extended Lifetime Scenarios and Their Respective Baseline

Scenario Name	Time Horizon	Cumulative Impact	Percent Change Compared to Baseline
		W/m^2 yr	
Two cycles of typical product use (Baseline for comparing 2x lifetime)	10 Years	4.7E-10	-
	30 Years	1.6E-09	-
	100 Years	3.8E-09	-
Extended Product Lifetime 2x	10 Years	3.4E-10	-28%
	30 Years	1.1E-09	-30%
	100 Years	2.7E-09	-30%
Three cycles of typical product use (Baseline for comparing 3x lifetime)	10 Years	4.9E-10	-
	30 Years	2.2E-09	-
	100 Years	5.6E-09	-
Extended Product Lifetime 3x	10 Years	3.4E-10	-31%
	30 Years	1.4E-09	-40%
	100 Years	3.4E-09	-41%

CONCLUSIONS

1. Using dynamic greenhouse gas (GHG) accounting and dynamic life cycle assessment (LCA) provides quantitative measures of how temporarily storing carbon can help achieve short term climate change goals. This data may be beneficial in future policymaking decisions, as the associated climate benefits of bioproducts like cotton are more significant under shorter time horizons.
2. Using dynamic LCA to evaluate the temporary biogenic carbon uptake of biobased products allows for a more nuanced analysis of climate benefits in both the short- and long-term time horizons.

3. The differences between dynamic LCA and static LCA are more pronounced when examined under shorter time horizons (*e.g.*, 10-years). Thus, time horizons should be a key factor to consider when evaluating interventions to mitigate the impacts of climate change.
4. When examining interventions that improve cotton sustainability, such as in the Climate Smart Cotton scenario (*i.e.*, cover cropping, no-tillage, and nutrient management), the use of dynamic LCA provides further context and more accurate depiction of climate benefits (*e.g.*, providing a 105% reduction in cumulative radiative forcing at 100-years).
5. Using dynamic LCA over traditional static methods provides consistent temporal boundaries and more accurate estimates of the short-term climate benefits of temporary biogenic carbon uptake illustrated by reduced cumulative radiative forcing compared to baseline conditions (up to 22% reduction after 10-years). When focusing on the benefits of biogenic carbon uptake and storage (with manufacturing and use phase impacts removed), the reductions are greater (up to 53% after 10-years).
6. Extending the lifetime of garments by 2x and 3x provides significant climate benefits of up to 30% and 41% reductions in cumulative radiative forcing respectively compared to the alternative baseline of creating 2 and 3 sets of new garments.

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