Physical Climate Risk for Global Cotton Production

Global Analysis

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COTTON 2040

ACCLIMATISE
building climate resilience
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Cotton 2040 Project Lead:

Hannah Cunneen

Forum for the Future

3rd Floor, 22-26 Paul Street

London, EC2A 4QE

United Kingdom

h.cunneen@forumforthefuture.org

Cotton 2040 Technical Lead:

Erin Owain

Willis Towers Watson

51 Lime Street

London, EC3M 7DQ

United Kingdom

Erin.Owain@willistowerswatson.com

Authors:

Uma Pal

Amanda Rycerz

Álvaro Linares

Approved by:

Alastair Baglee

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Convened by Forum for the Future with support from Laudes Foundation, Cotton 2040 is a multi-stakeholder initiative with a mission to facilitate the shift to a sustainable global cotton industry which is resilient in a changing climate; which uses business models that support sustainable production and livelihoods; and where sustainably produced cotton is the norm. *Find out more: https://www.forumforthefuture.org/cotton-2040.*

This global analysis is one of two reports published as part of the Cotton 2040 Climate Adaptation workstream. An additional study provides in-depth analysis of physical climate risks and socio-economic vulnerabilities to the cotton value chain in India. Both reports, alongside an interactive climate impacts map and supporting resources are available at *http://www.acclimatise.uk.com/collaborations/cotton-2040/*.

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Foreword

Welcome to the **Physical Climate Risk Assessment for Global Cotton Production** report, which focuses on the climate risks to cotton growing and production around the world. This work was completed by WTW in partnership with international sustainability non-profit Forum for the Future, as part of the Cotton 2040 initiative. This global report, a flagship publication for Cotton 2040, is complemented by a detailed India report that explores the relationships between physical climate risks and socio-economic vulnerabilities. Both reports are generated in response to the lack of comprehensive, readily available information about how the climate crisis is likely to impact cotton production, its supply chain, and the nature of the industry over the coming decades.

The Cotton 2040 initiative was originally established to bring together existing initiatives in the cotton sector to align around critical issues for - and accelerate the transition to - long term sustainability. In the context of climate breakdown, this goes beyond standards, certification or corporate commitments. Whether adequately prepared or not, the cotton system will be forced to change in the face of the dramatic changes that our warming climate will catalyse. With this report, our intention is to offer this data and analysis to spark a dialogue that will lead to joined up and informed action, and resilient responses that are deliberate, collaborative and systemic.

This report starkly demonstrates that by 2040 half of global cotton growing regions will face high or very high climate risk exposure to at least one climate hazard. Some regions are set to be exposed to up to seven climate hazards, from extreme temperatures to droughts, floods and wildfires, which is likely to lead to complex and converging risks as these threats intersect. In four out of six of the world's main cotton producing countries, climate change will lead to high or very high climate risk exposure. This threatens the entire cotton value chain. Climate risks are not only affecting cotton growing; extreme high temperatures affect worker wellbeing in the production cycle too.

The vast majority of cotton growing regions will be exposed to some degree of meteorological drought by 2040 and water scarcity is set to be one of the most significant climate risks for the world's most productive cotton growing regions, adding extra pressure to a fibre already under scrutiny for its water footprint. Many cotton growing regions are set to experience insufficient rainfall, while others will experience extreme and more intense rainfall leading to flooding and crop failures. These pressures present enormous difficulties for farmers and other actors across the value chain. Coping with them will require a response that goes beyond incremental solutions to fundamental changes. We need to radically rethink where, how and why cotton is produced and traded, and what the future holds for this economically and culturally important fibre.

The cotton industry, like many others, is unprepared for the changes that the growing climate crisis is bringing. Already, the sector is hard-pressed to address deeply entrenched environmental, social and economic challenges across its supply chains; these pre-existing vulnerabilities and inequalities will be exacerbated and accelerated by a warming climate. In other words, those actors and elements of the value chain that are already vulnerable will come under even greater pressure, and suffer increasing stress. Most industry-wide conversations and plans don't begin to address the scale of change that the climate crisis, if it continues on its current course (and even if ambitious steps are taken now) will force upon the industry, and the world.

Whilst Net Zero commitments made by countries and companies are establishing clear climate change mitigation pathways, at present the full sum of commitments are insufficient to keep the world within 1.5°C of warming above pre-industrial levels. This means that organisations across the cotton value chain need to simultaneously make bold commitments and take urgent action to decarbonise through their mitigation plans, whilst also developing robust adaptation plans to be prepared for the effects of the climate crisis. Navigating planning for these multiple potential futures - the one we must aim for through mitigation efforts, and the ones we must nonetheless be prepared for through adaptation planning - is the critical challenge that the cotton sector is facing.

This is not just a theoretical exercise for the future. Change is not just on the horizon, it's happening now. In India there is already a clear pattern of an increasing number of days over 40°C, and changes to the monsoon patterns resulting in extremes of floods and droughts. In Pakistan, and Australia, cotton crop failures have already been attributed to climate change. The trend towards increasing unpredictability and volatility of weather events is already in play. We are on the pathway to a different world, and the changes will only accelerate.

A systemic threat requires systemic solutions. In considering the impacts of climate change, it is critical to emphasise that if we are to develop an adequate response, our focus needs to look well beyond understanding the changes in the weather. We need to not only find ways to build environmental and social resilience into supply chains, but halt the downward spiral of the most vulnerable which will cost humanity and society so much more over time. Humanitarian crises have clearly demonstrated the economic argument for investing in resilience to avoid greater costs in responding to disasters.

Both environmental and social impacts of climate change will affect the entire cotton value chain and cannot be tackled in isolation. The information in this report needs to be considered not just for the changing environmental context for cotton production, but for how the impacts of climate will affect actors all along the supply chain. There are darker possibilities to factor in, such as the likelihood of societal disruption fuelled by resource scarcity or unequal distribution, leading to conflict or even war. All of this will have impacts not just on production, but transportation and distribution of goods, and beyond. The assumptions on which current supply chains are based cannot be presumed as a viable or predictable part of the future.

We urge people and organisations involved in the cotton industry to use this data and analysis to think radically about the future of cotton. No brand, retailer or trader will be able to avoid climate risk exposure in its supply chain; organisations must responsibly decarbonise their operations and supply chain impacts globally as quickly as possible, and centre climate impacts in their sourcing strategies. But we particularly call for the report to be used as a collaborative resource to make decisions together about how the industry needs to work, from how cotton is produced, transported, and used; to strategies, business models and more. We offer this report as a tool to inform thinking, and action, about mitigation as well as adaptation. The information it presents calls for nothing less than a collective reimagination and transformation of the cotton value chain to be sustainable, resilient and just.

Charlene Collison and Hannah Pathak, Forum for the Future

Part A: Background, context and research objectives

This section begins by presenting an overview of global cotton production and a summary of cotton's main climate sensitivities. The section then presents examples of past extreme weather events and climate hazards which have directly and indirectly impacted cotton production and implicated the wider cotton value chain (referred to henceforth as CVC). Moreover, other key drivers of change in global cotton production are discussed, which include political, economic and social drivers. Lastly, a rationale is presented which demonstrates the urgent importance of exploring the impact future climate change will have on cotton growing regions and thus on global cotton production, highlighting the need to take urgent action.

1. Background

1.1. Overview of global cotton production

Cotton is the most widely produced natural fibre. A total of approximately 25 million metric tonnes (Mt) of cotton is produced worldwide per year, with a market worth of about 12 billion dollars.[i] Its fibre, which serves as the raw material for approximately 31% of the global textile market, has a yearly economic impact of at least $600 billion.[ii] Agriculture is the main contributor to the Gross Domestic Product (GDP) of most countries, especially developing countries, with cotton being a key agricultural crop. Due to its direct reliance on the state of the climate, agriculture is highly vulnerable to climate change due to shifts in rainfall patterns, temperature increase, and increase in intensity of extreme events.[iii] Impacts of climate change on cotton production in cotton growing countries will undermine livelihoods and lead to global demand supply gaps, price volatility and spikes, and create implications for the wider CVC.

Global cotton production has increased from 18.95 Mt in 1990 to 26.40 Mt in 2019.[iv] Average yields have relatively plateaued since 2004 as many countries struggle with pest and water problems, and yet future global cotton production is projected to increase to a total of 29.12 Mt by 2028 to meet market demands.[v] It is therefore projected that future production increases will be a result of expanding of cotton growing landmass, rather than enhanced productivity.[vi]

The top five cotton-producing countries are India (6.2 Mt), China (5.7 Mt), United States (4.1 Mt), Brazil (2.4 Mt) and Pakistan (1.8 Mt) for the year 2019-2020, which together account for more than 75% of global production.[vii] These are followed by Australia, Uzbekistan, Turkey, Turkmenistan and Burkina Faso. The nature of cotton production and the current trends differ between these countries. Although India is the number one contributor to the world's total cotton production, its yield per acre is relatively low.[viii] China is the largest consumer of raw cotton, followed by India[ix]. The United States of America is leading in cotton exports, and Pakistan is both a major consumer and producer. Brazil is also a main cotton exporter while Australia is renowned for producing good fibre length and colour.

There are four species of cotton grown globally. *Gossypium Hirsutum,* also known as 'upland cotton' accounts for 98-99% of commercial cotton grown today. *G. Barbadense*, also known as 'Egyptian cotton', is a high-quality variety, and is predominantly grown in Israel, Western USA, Sudan, Turkmenistan, South India, Peru, China and Uzbekistan. *G. Arboreum,* also known as 'desi cotton', is predominantly grown in India, Pakistan, Myanmar and Thailand. Lastly, *G. Herbaceum,* also known as Levant cotton, is native to southern Africa and the Arabian Peninsula but is predominantly grown in India and Iran.[x] Genetic engineering has produced different varieties of cotton over recent years, such as Bacillus thuringiensis (Bt) cotton, which is being grown extensively across both India and China[xi].

1.2. Cotton's key climate sensitivities

Cotton (Genus: *Gossypium*) is grown predominantly in hot and dry climates, however it is sensitive to various climatic parameters during different stages of crop development, including temperature and rainfall. Gradual changes in climate parameters, rapid shifts in extreme weather events, and increase in climate hazards all present increased risk to cotton cultivation.

Cotton has adapted to survive in temperate sub-tropical and tropical environments and is considered to be relatively resilient to drier and hotter conditions due to its vertical tap root.[xii] Various stages of crop development are sensitive to different temperature thresholds. While optimal germination is reached at temperatures of 18°C to 30°C, with a minimum of 14°C and maximum of 40°C[xiii], temperatures between 27°C and 32°C is optimum for boll development and maturation, with yields greatly reduced above 38°C.[xiv] Cotton has been known to grow at temperatures of 41.8°C in regions in northern India as heat tolerant varieties are capable of withstanding extreme temperatures for short periods of time given that water is readily available. While it has not been established that 41.8°C is the upper limit, heat stress is a big constraint to increasing yields. Increasing global temperatures due to climate change may exceed cotton's upper temperature tolerance threshold, exposing the crop to enhanced heat stress, and impacting cotton yield and quality.[xv]

The length of the total cotton growing period is about 150 to 180 days,[xvi] varying according to local conditions and cotton varieties. The long growing season is a reason why cotton is so susceptible to disease and pests. While increasing atmospheric temperature may present an opportunity for some regions by lengthening the potential cotton growing season, regions which are already growing cotton in conditions close to the upper temperature tolerance threshold may be at significant risk. Furthermore, a warmer climate will present favourable conditions for pests and diseases, presenting a further threat to cotton.

In addition to specific temperature requirements, cotton is also sensitive to specific rainfall requirements at specific stages of crop development. During the early stages, relatively less water is required at 2 – 4 mm of water per day, however water requirements increase during leaf development and flowering best at 5 – 7 mm per day.[xvii] On average, cotton requires between 700 – 1300 mm of water throughout the growing period[xviii], with a minimum of 500 mm suggested as a minimum threshold by some sources.[xix] This ranges considerably across the world from a low of 300 cubic meters of water per hectare per season throughout the growing season in Israel, to 12,300 cubic metres per hectare per season in Sudan.[xx] While cotton is considered fairly drought tolerant as it is deep rooted with tap roots up to 3 metres deep, it is critical that the crop receives adequate water supply during these specific stages of crop development. Climate change is projected to increase rainfall in some regions while decreasing rainfall in other regions. Rains are projected to become more erratic and less reliable, increasing the risk to cotton.

At the other end of the spectrum, cotton is sensitive to excessive moisture and water logging, especially during the early season. Although the crop is relatively resistant to short periods of waterlogging, extreme rainfall events can lead to waterlogged conditions and flooding, which can inundate cotton plantations and cause widespread damage to agricultural crops. Continuous rain during flowering and boll opening will impair pollination and significantly impact the quality of the cotton fibre.[xxi] Heavy rainfall during flowering causes flower buds and young bolls to fall.[xxii] Heavy rainfall can also cause significant damage to soils, leading to soil erosion, the loss of nutrients from the soils, and increased run-off.[xxiii]

Periods of extreme rainfall events can saturate soils, reduce the frictional shear resistance of the soils, and may trigger debris flows or landslides in hilly regions. Depending on the debris to water ratio, debris flow or landslide can cover extensive area and submerge any feature in its path. In rural regions, this may include agricultural fields, the damage to which can be detrimental to the survival of the crop with knock-on impacts on livelihoods. Climate change is projected to increase the intensity, frequency and duration of extreme rainfall events across some regions of the world, which in turn may increase the risk of landslides in these regions.

The combination of long periods of high temperatures and dry conditions can create the conditions required for wildfires. If dry fuel is plentiful, wildfires can spread extensively and rapidly causing significant loss and damage to human life and the rural community, to key infrastructure including utilities and transport routes, and to agricultural crops and livelihoods. Climate change will increase the intensity and frequency of wildfires across regions projected to experience warmer, drier conditions.

Delicate young cotton seedlings can also be impacted significantly by strong winds, which may be associated with cyclones, tornadoes and hurricanes, as damaging wind speeds can 'sand-blast' the seedlings, uproot the plant during early stages, blow fibre away from opened bolls, erode topsoil due to wind-erosion, and damage the quality of the cotton boll fibre by covering it in dust particles.[xxiv] Impacts on key infrastructure may further impact cotton cultivation, for example by causing damage to electricity supply and irrigation systems which may restrict the ability of the farmer to tend to the crops, and cause trees and debris to block critical infrastructure routes. While the confidence in model abilities to project wind strengths are currently low, there are suggestions that a warmer climate may give rise to stronger winds in some regions such as northern Europe due to a shift in due to the change in the large-scale atmospheric circulation, while a decrease is projected across other regions such as southern Mediterranean regions.[xxv] Furthermore, an increase in extreme weather events, such as tornadoes, cyclones and hurricanes, is projected to occur across some regions of the world[xxvi], increasing the risk of damage to cotton crops from strong winds.

2. Context: Drivers of changes and implication on wider CVC

Fluctuations in cotton yield are driven by a variety of factors ranging from global politics, to climatic events to pandemics, and so forth. This section begins by presenting examples of climate events and hazards which have impacted national production and have had a knock-on effect on the wider CVC. Key global and national policies around cotton are then presented.

2.1. Extreme weather events, climate hazard and environmental challenges

Sudden and extreme changes to the weather system, such as heavy rainfall, extreme snowfall and heatwaves; or secondary climatic hazards, such as precipitation-induced landslides, wildfires, or flooding, can all have a significant impact, not only on national cotton production and the CVC, but also have a knock-on effect on international cotton production. Climate change is projected to increase the intensity, frequency and duration of extreme weather events and climate hazards.[xxvii] Below are examples of various extreme weather events and climate hazards which have had a significant impact on cotton production in various countries in the last few decades.

2.1.1. Pakistan flooding, 2010 and 2011

In 2010 and again in 2011, heavy downpours led to widespread flooding of Pakistan's cotton fields. The 2010 floods inundated 160,000 km^2 (approximately 1/5 of the nation), and caused 35 billion Euros worth of damage, leading the United Nations (UN) to declare it as one of the worst humanitarian disasters in UN history. Losses from cotton crops accounted for nearly 75% of all financial losses with one-fifth of the crop destroyed, severely impacting livelihoods of small-scale farmers, and workers across the CVC, especially Pakistan's textile manufacturing sector.[xxviii] Poor cotton production in Pakistan significantly impacted the global cotton market, with Pakistan being one of the world's largest cotton producer. Indeed, cotton sourcing of cotton became more difficult and costly for retailers.[xxix] In 2010, cotton prices rose from a stable 10-year price of approximately US $0.65–0.70 per pound of cotton in 2009 to spike as high as US $2.48 on some shipments, with the flooding being a major contribution to this price increase.[xxx] Prices took months to resume to previous market rates. Climate change was stated as a major contributing factor to the flooding event by the Pakistan Government and the UN.[xxxi]

Pakistan's cotton industry has been struggling to adapt to climate change over the past decade, with production losses greater than 25% between 2011-2019.[xxxii] Over the coming decades, not only is Pakistan's cotton facing increasing stress due to projected increase in extreme rainfall events, but Pakistan is also facing the longer-term threat of water scarcity due to projected increase in drought during some months of the year. This will make it increasingly difficult for farmers to access adequate water for irrigation.

2.1.2. Australia wildfire, 2019

The 2019-2020 wildfire season in Australia was especially long, with major fires starting in September 2019, even before the official arrival of spring. The country experienced a humanitarian crisis and it is estimated that over 10 million hectares of land was burnt across much of the eastern portion of the country, with 34 fatalities and destroying 3,500 homes.[xxxiii] Not only did Australia register its hottest year on record in 2019, but the year was also the driest year on record with average rainfall of 277.63 mm for the year, which compares to the previous record low of 314.46 mm.[xxxiv] Water scarcity and hot conditions placed Australian cotton under significant stress. During the previous year, dryland cotton acreage began at just below 163,000 hectares, however in 2019/2020, only approximately 35,000 hectares was planned.[xxxv] This had a major knock-on impact on world trade. During the past three years, Australia contributed to 3.63 to 3.92 million bales to global cotton production annually, however during 2019/2020, Australia will contribute less than a million bales, the lowest production since 1982/1983.[xxxvi]

2.1.3. Hurricanes in Texas

The United States grows 25% of the world's cotton, with Texas producing approximately 50%.[xxxvii] Over recent decades, the southern regions of the United States have not only faced increasingly dry conditions and longer periods of drought but have experienced numerous disastrous hurricanes. The extensive losses and damages both economically and socially resulting from these extreme weather events and climate hazards have impacted not only the national cotton production but have has a knock-on impact on world cotton trade and the wider CVC.

In 2011, Texas experienced severe drought conditions, which caused 55% of cotton fields to be abandoned, leading to a financial loss of about USD 2.2 billion.[xxxviii] The devastating impacts of water scarcity meant that millions of acres of crops did not receive enough water for seeds to germinate. Due to low production, Texas lost sales to the Asian markets, as well as to other cotton producing countries, such as Brazil and Australia. While the Southern Plains experience droughts as part of natural climate variability, the intensity of drought events is projected to increase in the future due to the impacts of climate change.[xxxix] This poses a serious challenge for cotton production in Texas and the United States.

In 2017, Hurricane Harvey decimated parts of south-central Texas. The category 4 hurricane bought winds in excess of 130 mph (215 km/h), and over a 4-day period, many areas received more than 40 inches (1,000 mm) of rain causing unprecedented flooding.[xl] The hurricane caused more than $100 million in damages to cotton crop by either completely destroying the cotton or degrading the quality of the cotton bolls which were ready for harvesting.[xli,xlii] In total, the hurricane was the second most costly hurricane in US history, second only to Hurricane Katrina in 2003, representing $125 billion in damages primarily from catastrophic rainfall-triggered flooding.

2.1.4. Extreme rainfall in India

Over the last few decades, the cotton sector in India has been severely impacted by extreme weather events and climatic changes. In 2009, three days of torrential rains brought flooding across Punjab and submerged cotton farms in 60-70 villages in the Sri Muktsar Sahib region. Cotton fields were under 1.2 - 1.5m (4-5 feet) of water and flood water did not retreat for months, making it impossible to grow cotton in the 2010 season. Due to a repeat of the disaster in 2011, farmers in Sri Muktsar Sahib decided to plant rice paddies instead of cotton, as rice crop can withstand water-logged conditions better than cotton. This an example of how cotton farmers in some regions are already turning away from cotton cultivation due to a changing climate. Farmers state how the monsoon rainfall used to be spread across the season, but have become more intense and frequent following dry spells.[xliii] The 2017-2018 Economic Survey carried out by the Government of India projects that extreme rainfall could reduce cotton farmers income by 13.7% in the Kharif season, and 5.5% in the rabi season[xliv], which may poses a significant threat to national production.

2.1.5. Water abstraction

Cotton is a water-intensive crop, with some experts asserting that it demands the largest water use among agricultural commodities.[xlv] Water-diversion for cotton production, and the pollution of water bodies caused by cotton-growing has severely damaged water bodies in Central Asia (Aral Sea), Pakistan (the Indus Delta) and Australia (the Murray Darling River), and harmed the people and biodiversity that depend on them.[xlvi] In Central Asia the Aral Sea was once the fourth largest inland body of water in the world, covering 66,000 km^2, but since the 1960s has reduced to less than 10% of its pre-1950's volume, due to irrigation demand for cotton production. Between 1953-1964, the land surrounding the sea was converted to cotton fields, and over 75% of the water was diverted to cotton fields.[xlvii] In Australia, the death of over a million fish in the Lower Darling River System has been linked with water abstraction for cotton irrigation during periods of drought.[xlviii] Encouragingly cotton farmers worldwide are adopting better management practices to reduce water abstraction and agrochemical use. Prior to the Better Cotton Initiative, 97% of water in the Indus River Basin was abstracted for agricultural production, including cotton. Through the initiative, Pakistani farmers have reduced water abstraction by nearly 40%, thereby reducing demands on the Indus River.[xlix]

2.1.6. Soil, water and biodiversity contamination

Heavy and often indiscriminate use of agrochemicals (pesticides, fertilisers) for cotton mono-cropping damages soil fertility and causes runoff into rivers, lakes, wetlands and aquifers, contaminating water sources and the biodiversity that depends on them through immediate or long-term toxicity. The excessive use of chemical fertilisers and pesticides in Central Asia have converted the landscape of the former Aral Sea into one of the most toxic and saline places on earth. In the Namoi Valley, the cradle of Australia's cotton industry, widespread agrochemical use from the 1960s, including the use of DDT, has caused extensive soil and water contamination that persists today. In Australia, and worldwide, initiatives that promote reduced agricultural inputs and water use, and programs targeted at land and water remediation can help reconcile previous malpractices. Cotton Australia, an industry trade group, the Cotton Research and Development Corporation, along with prominent retail brands and farmers, launched a program to restore local ecosystems in the Namoi Valley, through erosion reduction and water quality improvements, to conserve the land and biodiversity.[l]

2.2. Global and national cotton and climate adaptation policies and strategies

2.2.1. Global policies

Top-down global policies are heavily export and trade focused. While negotiations under the WTO aim to reduce trade disparities, enhance domestic reforms and policies, and ensure better support for developing countries, the impacts of climate change on the CVC and the losses entailed by them are missing from the global cotton policy landscape. There exists voluntary agricultural global organisations and alliances such as the Global Alliance for Climate Smart Agriculture (GACSA), and ongoing initiatives such as the Better Cotton Initiative which incorporate sustainability considerations and address some of the impacts of climate change. However, climate change does not find adequate mention in global governmental negotiations for commercial crops such as cotton. Currently, most studies on the impact of climate change on cotton are standalone, with no global mandate or guidelines for enhancing resilience of the CVC to climate change.

That cotton is grown in more than 75 countries demonstrates its critical importance in livelihood generation, foreign exchange earnings and maintaining economic stability for cotton growing countries, especially least developed and developing countries.[li] Cotton is central to global agricultural trade discussions, specifically in terms of trade reforms required to address existing cotton trade barriers and assistance required in the cotton sector in developing countries.[lii] Over a number of years various summits or initiatives have focused on risks and opportunities to cotton. The 2003 Cancun Ministerial Conference, which recognised the need to address the risks and opportunities for cotton "ambitiously, expeditiously and specifically"[liii], was a landmark in global cotton trade. Since then, not many concrete measures have been agreed upon, apart from the removal of export subsidies in the United States.[liv] In 2004, a special cotton subcommittee was created under the World Trade Organisation's (WTO) Committee on Agriculture in Special Session to lead on cotton specific discussions.[lv] Following this, the 2005 Hong Kong Ministerial Declaration suggested that all export subsidies for cotton be eliminated by developed countries in 2006, however, this deadline was missed.[lvi] Global cotton trade negotiations have been stymied by lack of consensus between the US, the EU, and China and the developing countries, with the US's focus on tariff and non- tariff barriers and synthetic fibres, and the tariff concessions that China may face.[lvii]

The issue of decline in cotton trade prices and knock-on impacts across the CVC can be solved by addressing demand supply imbalances, caused by various issues such as weak consumer and market demand, decline in economic activity and insulating domestic measures which lead to increase in cotton production despite decline in global market prices.[lviii] To address such challenges, the 2013 Bali Ministerial Conference[lix] initiated discussions to improve transparency and monitoring of cotton trade and examine trade related developments in terms of market access, domestic support, and export competition. This was further emphasised in the 2015 Nairobi Ministerial Decision on Cotton[lx], under which cotton growing countries also committed to grants, based on their trade policies and abilities, duty free and quota free market access for cotton and cotton related product exports from Least Developed Countries. Ministries also committed to abolish cotton export subsidies by 1 January 2017. The Nairobi decision also emphasises the need for more efforts to reform domestic cotton policies in WTO member countries.[lxi]

2.2.2. National policies

Recognising the importance of cotton cultivation and the CVC for GDPs, cotton has found mention in varying degrees in different plans, strategies, and surveys of three of the five top cotton growing countries, namely, Brazil, India and Pakistan. On a local scale, there is inadequate understanding of how national and local policy landscapes may impact the CVC – for example through regulatory measures such as water and irrigation policies, market schemes, etc.[lxii]

Brazil's National Adaptation Plan to Climate Change[lxiii] states that climate change could impair large scale and family farming in the country and production of key crops, including cotton. The National Adaptation Plan mentions the Harvest Guarantee Programme through which the Federal Government directs financial compensation to farmers, where there are cases of production losses due to drought or excessive rain of crops such as cotton.

India's Economic Survey 2017-18[lxiv] dedicates a chapter to 'Climate, Climate Change, and Agriculture' which, based on historical district level data on temperature, rainfall and crop production, estimates a 4% decline in agricultural yield of Kharif crops[1] (including cotton) due to extreme temperature shocks and 12.8% due to extreme rainfall shocks. These are 7% and 14.7% respectively, for unirrigated Kharif areas.[lxv] The Survey also identifies that the key challenges faced by broadly non cereal crops, including cotton, in central, western and southern India are inadequate irrigation facilities, dependence on rainfall, ineffective procurement and insufficient investments in research and technology.[lxvi] However, the country does not have specific policies or strategies targeted at addressing the impacts of climate change on cotton cultivation.

Pakistan's Second National Communication on Climate Change[lxvii] identifies cotton and cotton yarn as a major source of the country's export earnings and source of livelihoods. The document states that erratic weather patterns exacerbated by the impacts of climate change, heat and water stress have contributed to the reduction in cotton production in the country. Ongoing measures in the country, as mentioned in the National Communication, include rainwater management in cotton fields to minimise the impact of climate change.

The price of cotton can be highly volatile due to a range of factors including supply and demand, stockpiling, national regulation, trade relations, and national subsidies. In combination with other factors, this can drive significant turmoil throughout the entire CVC.[lxviii]

Higher stock-to-use ratios can have a significant impact on cotton pricing, with national stockpiling of cotton yields significantly distorting global prices. In China, between 2011-2013, a government-backed programme offered the nation's farmers a premium for home-grown cotton which led to a surplus of an estimated 40 million bales of cotton, held in reserves. Over the next several years, as global cotton prices fell from a record high in 2011, China stockpiled cotton rather than selling it, yet as stockpile volumes increased, the global price continued to fall. During this period China also halted imports from cotton-producing nations. Global cotton prices fell by 9.5% from the summer of 2015 to March of 2016.[lxix]

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[1] *Kharif crops in India are usually sown during June, at the advent of the monsoons.*

Tariff and trade restrictions, particularly among the world's major superpowers, can have a significant impact on the global cotton market. The on-going trade war between the United States and China has resulted in a 25% tariff on cotton imports for both countries. As U.S. cotton exports to China have plummeted, the price of U.S. cotton has fallen by roughly 30%, and U.S. stockpiles are the highest that they have been in a decade.[lxx]

National policies and subsidies can create national advantages although distort global markets and trade. For example, in China the government established a subsidy for cotton farmers in Xinjiang province to ensure stable production and the global competitiveness of China's cotton. If the market value of cotton falls below the state-set price, the government makes up the difference.[lxxi] Yet China's policies have faced criticism from World Trade Organization (WTO) member nations for providing a subsidy beyond what WTO regulations permit, thereby showing preferential treatment of national producers and distorting global markets.[lxxii]

3. Rationale and research objectives

Greenhouse gas emission reductions are essential to avoid the worst effects of climate change being experienced over the longer term. However, regardless of future action on reducing emissions, society and ecosystems are already faced with inevitable changes in climate that will impact over the coming decades. In terms of the CVC, every stakeholder will be affected, from individual farmers and cooperatives and their communities, to large corporates and major brands.

Despite the ambitious goal as set out by the Paris Agreement to keep global warming "well below 2°C by 2050", to date, even the ambitious pledges and targets of countries around the world will only limit warming to between 2.2-3.4°C.[lxxiii] As it stands, current policies are being missed by the majority of countries around the world, meaning that warming of more than 3°C is probable by the end of this century. This will limit changes in our climate, but some change will inevitably continue to occur. However successful the world is with decarbonisation, the world is faced with decades of unavoidable climate change and changes for our oceans and cryosphere that are expected to be irreversible on timescales relevant to human societies and ecosystems.[lxxiv]

It is important to acknowledge that there may be some positive impacts of climate change of global cotton production, such as an increase in carbon dioxide potentially leading to increased photosynthesis and increase in cotton growth and yield[lxxv], or increase in average daily temperature may result in longer and better cotton fibre growth, with warmer temperatures at the beginning and end of growth seasons leading to an increase in length of growing period.[lxxvi] However, the potential positive impacts will only occur in environments where there is an absence of other climate hazards, an unlikely situation. Negative future climate change impacts include increasing number and severity of days experiencing very high temperatures (above 40˚C[lxxvii]) during the growing season, leading to decreasing photosynthesis, boll shedding and reduction in seed numbers per boll, heat stress is an important constraint to increasing yields[lxxviii], and lower rainfall (below 500mm[lxxix]) and relative humidity causing photosynthesis and growth to slow down.[lxxx]

The impact of climate change on cotton growth and yields will have knock on effects on the whole CVC as raw cotton is the key ingredient for cotton processing, spinning and weaving. Globally, the CVC is highly complex, with several actors at every rung of the value chain. Processing and yarn spinning are highly capital intensive and competitive due to the commoditised nature of yarn. Most industries along the CVC are fragmented, with lower economies of scale, and are heavily dependent on the quality and quantity of raw cotton supply. For example, climate change may impact the quality of cotton produced, as a wetter than average growing season may give rise to poorer cotton quality, and as a result, ginners may have to import better quality cotton to substitute the loss.

The main objective of this study will be to project future climate change across the world's cotton growing regions centred at 2040s. A worst-case emission scenario will be considered in order to explore the more profound changes in the climate. By addressing these vital gaps in the wider understanding of climate change impacts on the CVC, the first few steps are taken to build the platform for facilitating dialogue, initiating change and thus promoting action by encouraging the cotton industry, stakeholders, brands and retailers to prepare today to withstand current and future adverse climate impacts on global cotton production.

The methodology used in this study is detailed in **Appendix 1: Methodology.**

Part B: Results

This part presents the results of projected climate hazards across the world's cotton growing regions by the 2040s. The results for each of the individual climate hazard indicators are presented. For each indicator, a definition of the measure used for each indicator is provided, along with the absolute hazard level projected for 2040s, and the delta change in the indicator in either a positive or negative direction for 2040s relative to baseline conditions (2000-2019). **Appendix 2: Metadata table** presents a detailed meta-table which, for each indicator, defines the measure used, provides a detailed rationale behind each indicator and the source of the data used in this study. All delta changes in projections are derived relative to the baseline present day period defined as 2000-2019. All indicators are normalised, thus the results are relative to other cotton growing regions.

1. Individual global climate hazard indicators

1.1. Hazard 1: Heat stress: Increasing global temperatures exceeding cotton's optimum temperature range during the growing season

1.1.1. Indicator

Definition of the indicator: The indicator Effective Growing Degree Days (EGDD) is used as a proxy for the length of the growing season suitable for growing cotton. The EGDD is defined as the number of times temperatures is between 14°C and 30°C, i.e., the optimal temperature range for the cultivation of cotton.[i]

Relationship: A lengthier growing season than experienced during present day may be an opportunity for cotton farmers. A shorter growing season than experienced during present day arises as increasing temperature exceeds the optimal upper threshold suitable for cotton growing, 30°C. This in turn places cotton under heat stress, increases the demand on other resources such as irrigation demand, and gives rise to a shorter growing season, all of which present a risk to cotton cultivation.

1.1.2. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

A longer growing season is projected across the majority of cotton growing regions by the 2040s, however this change is relatively low (**Figure 1**). The growing season is projected to increase across central and southern Africa, eastern Australian, central South America, eastern coast of the US, central regions in India and throughout the majority of China, possibly presenting an opportunity in these regions for cotton cultivation. More specifically, the greatest increase in the growing season are projected around 15°S, in parts of southern Brazil, central Bolivia, Zambia, Zimbabwe, southern Angola and north-western India.

However, the greatest change in the length of the growing season is that of a shorting of the growing season across northern sub-Saharan Africa countries. A predominant decrease is projected across cotton growing regions in south-west Mali, south-east Senegal, throughout the majority of cotton growing regions in Burkina Faso and all cotton growing regions in northern Ghana. The growing season will also become shorter across the southern cotton growing regions in the state of Arizona in the United States, regions in central Venezuela and northern Colombia.

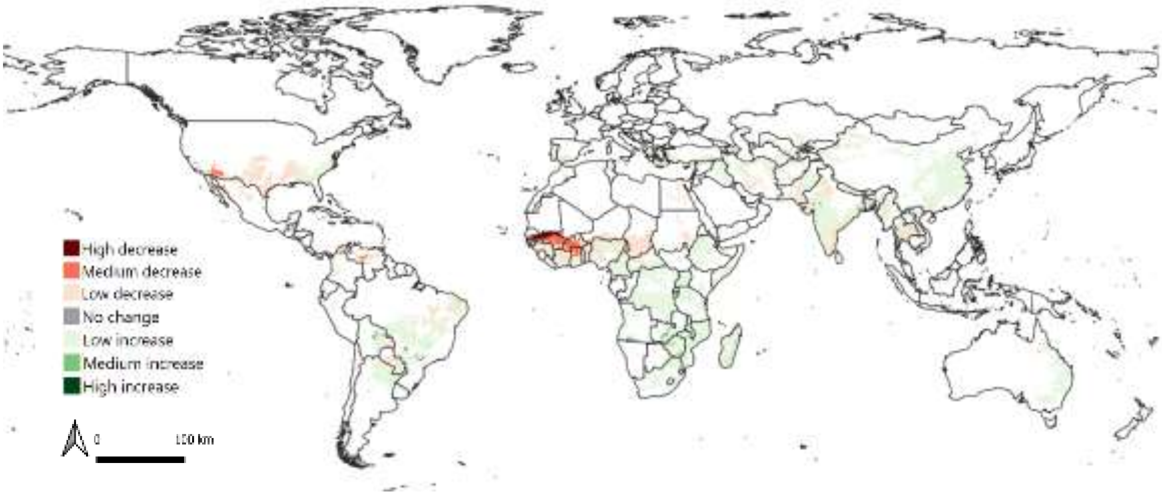

Figure 1. Projected change in Effective Growing Degree Days by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative against measures in other cotton growing regions.

1.2. Hazard 2: Heat stress: Increasing global temperatures pose a significant risk to cotton yields

1.2.1. Indicator

Definition of the indicator: This indicator is used as a proxy for the number of days in a given year when temperatures over 40 °C pose a significant risk to yields.

Relationship: The higher the projected number of days above 40°C, the greater the hazard presented to cotton.

1.2.2. Projected hazard for the 2040s

The highest number of days in a given year when temperatures exceed 40°C are projected to be experienced across regions of eastern Iraq and northern Sudan (**Figure 2**). Cotton growing regions across northern sub-Saharan countries, western Pakistan, hotspots in central India and southern Arizona in the US are also projected to experience a relatively high number of days above 40°C by the 2040s relative to other cotton growing regions.

There are no days when temperature is projected to increase above 40°C by the 2040s across cotton growing regions along the equator in central Africa, sporadic regions in Brazil along the western coast of Ecuador and Peru, and regions in eastern China.

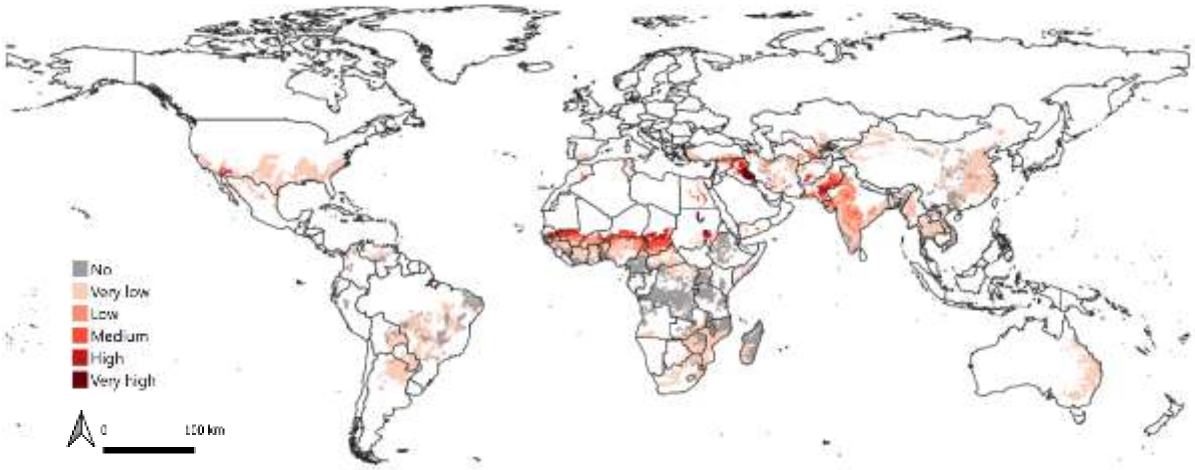

Figure 2. Projected number of days when temperature exceeds 40°C by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.2.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The greatest increase in exposure to high temperatures is projected to occur across southern Sudan and central Chad (**Figure 3**). The increase is also significant across the northern sub-Saharan regions of southern Chad, southern Niger, northern Nigeria, Burkina Faso, southern Mali and southern Senegal, and across regions in the Middle East in Syria, Iraq and Turkey, and across the majority of cotton growing areas in Pakistan.

No cotton growing region is projected to experience a decrease in the number of days above 40°C by the 2040s.

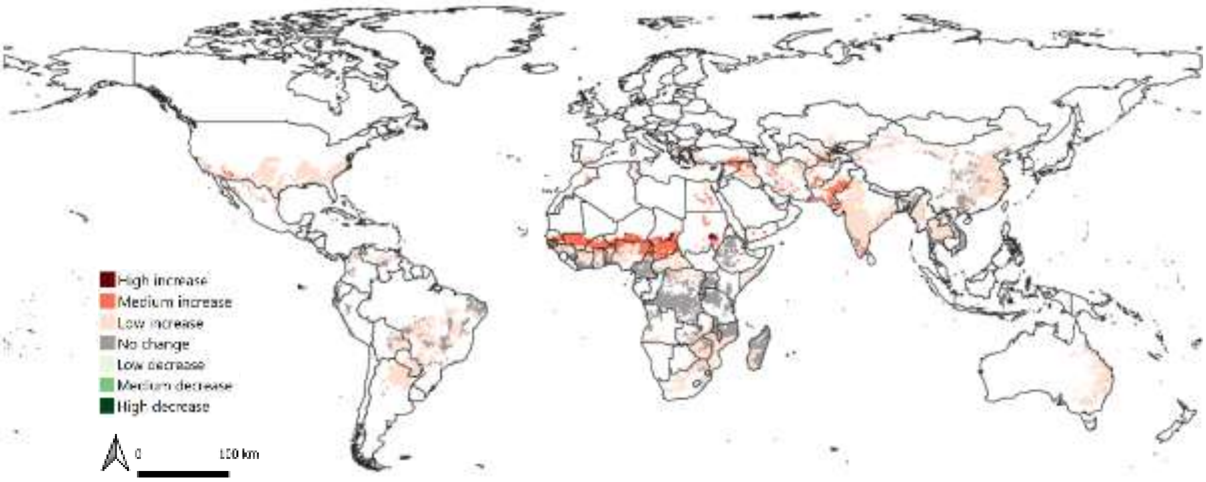

Figure 3. Projected change in number of days above 40°C for the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.3. Hazard 3: Short-term water scarcity (Meteorological drought)

1.3.1. Indicator

Definition of the indicator: The projected number of days when annual average 3-month standard precipitation index (SPI) is less than -1.5 for 2040s. This indicator is used as a proxy for 'severe' drought over a period of 3 months.

Relationship: The higher the projected number of days, the greater the exposure of cotton to severe drought.

1.3.2. Projected hazard for the 2040s

The vast majority of the global cotton growing regions will be exposed to some degree of meteorological drought by the 2040s (**Figure 4**). Cotton growing regions which are projected to experience a "very high" number of days of 'severe' drought are not clustered in a specific location and therefore identifying key hotspots and trends is difficult. It is clear, however, that drought will be a pan-global issue for cotton cultivators in the 2040s.

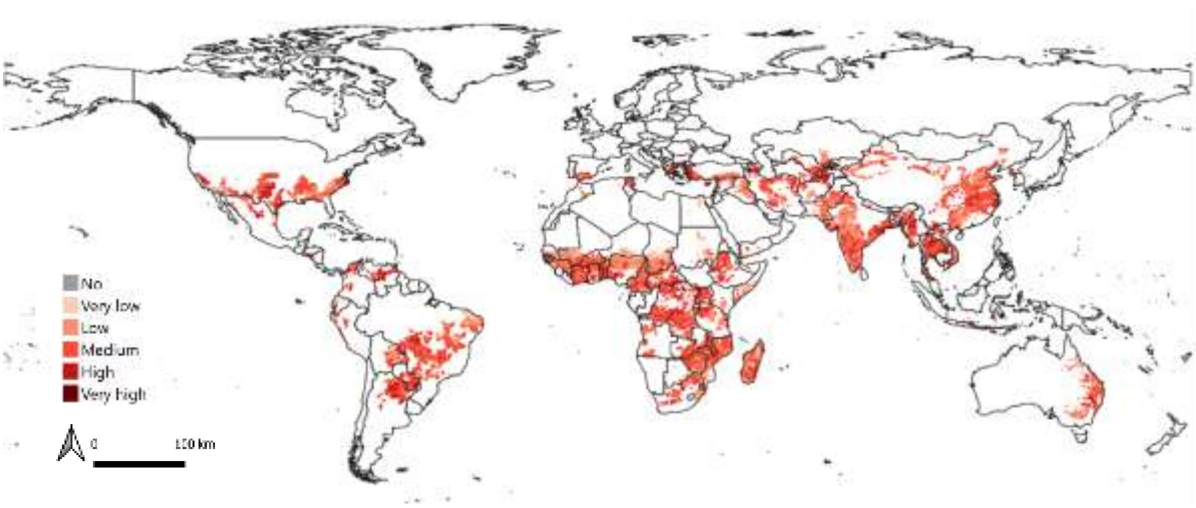

Figure 4. Projected number of days experiencing meteorological, short-term 'severe' drought for the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.3.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The majority of cotton growing regions across the world are projected to experience an increase in exposure to meteorological drought by the 2040s relative to present day conditions (**Figure 5**). However, a clear decrease in meteorological drought is projected for the Sahelian region in sub-Saharan Africa and is especially pronounced in cotton growing regions in southern Chad, northern Nigeria, and southern Mali.

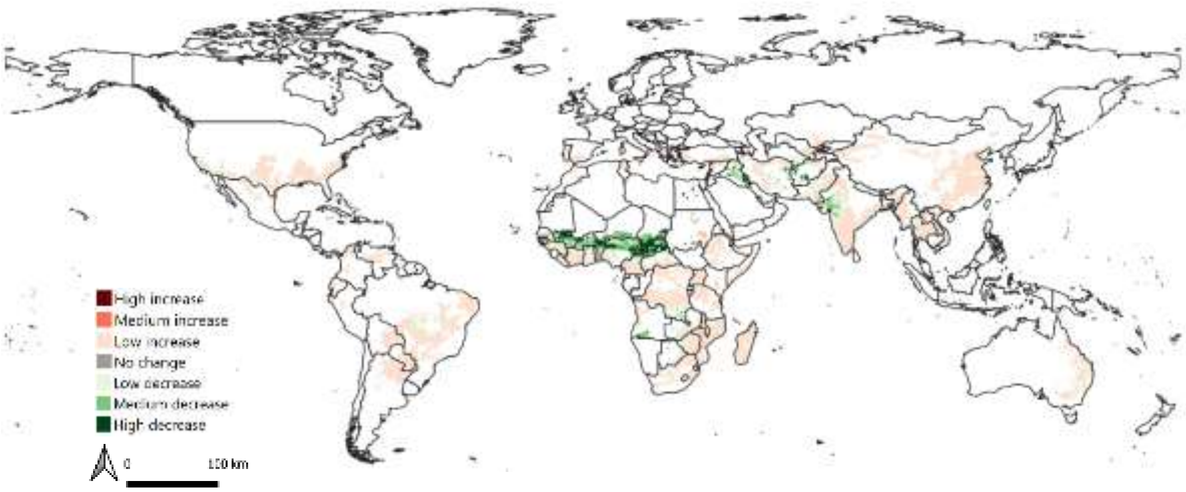

Figure 5. Projected change in number of days experiencing meteorological, short-term 'severe' drought for the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.4. Hazard 4: Long-term water scarcity (Hydrological drought)

1.4.1. Indicator

Definition of the indicator: The projected number of days when the average 18-month standard precipitation index (SPI) is less than -1.5 for 2040s. This indicator can be used as a proxy for 'severe' long term hydrological drought and an indication as to potential groundwater recharge where lower recharge suggests diminishing availability.[ii]

Relationship: The higher the projected number of days, the greater the projected hazard to cotton growing regions from long term drought and low groundwater levels.

1.4.2. Projected hazard for the 2040s

As with the previous indicator, exposure to hydrological drought is projected to be high by the 2040s (**Figure 6**). Cotton growing regions which are projected to be especially exposed to longer-term drought conditions relative to other cotton growing regions are located in the states of Florida

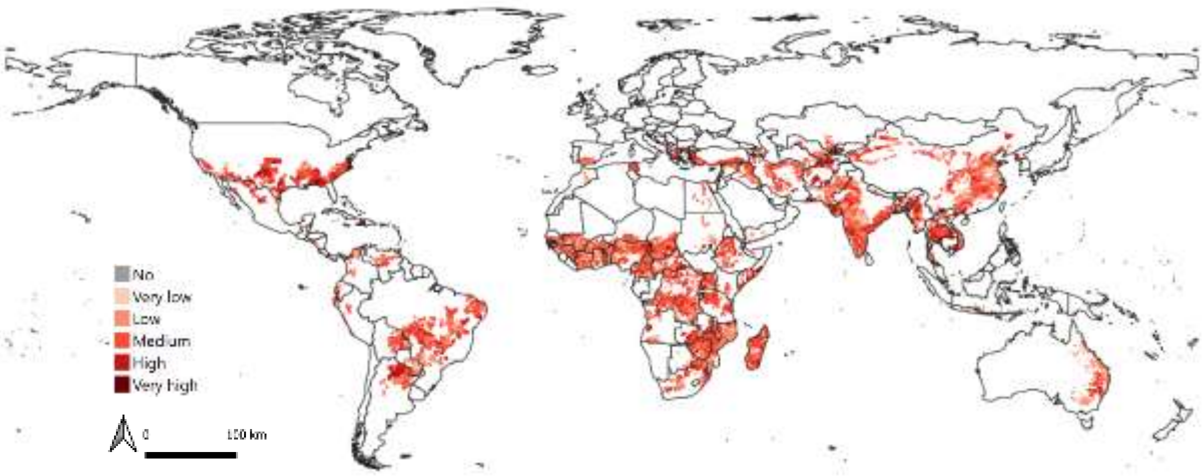

Figure 6: Projected number of days experiencing hydrological, long-term 'severe' drought for the 2040s

and Texas in the United States, northern Argentina, central Somalia, north-eastern Thailand, southern Vietnam, and in cotton growing regions in north-eastern China.

1.4.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The majority of cotton growing areas across the world are projected to experience an increase in longer-term drought conditions by 2040s relative to present-day conditions (**Figure 7**). However, the greatest change, regardless of the direction of change, is along the Nile River in Egypt, as the northern reaches are projected to experience a decrease in long-term drought conditions while the southern reaches are projected to experience an increase in long-term drought conditions. Eastern Australia also shows a regional trend across cotton growing regions in the state of Queensland which is projected to experience a "medium" increase in exposure to longer-term drought.

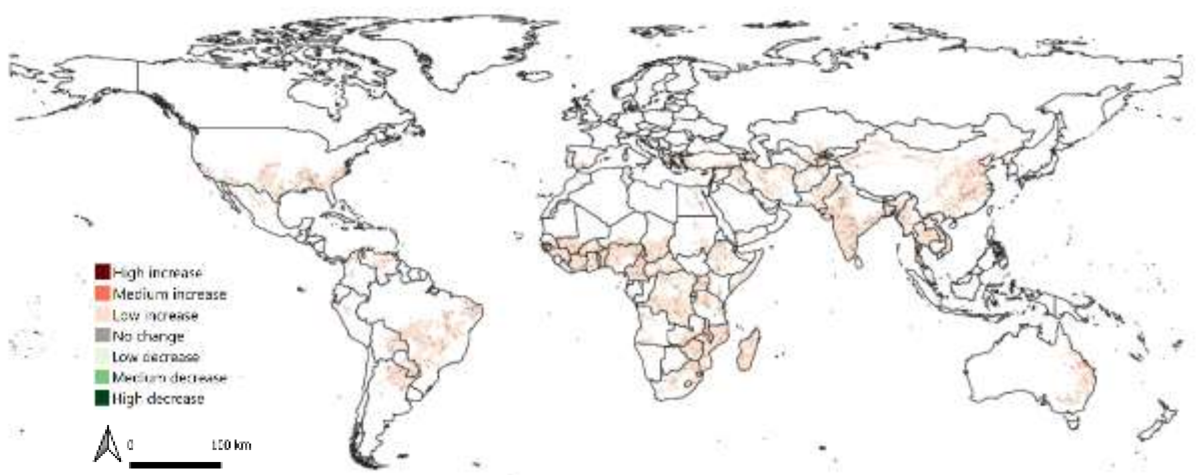

Figure 7. Projected change in number of days experiencing long-term 'severe' drought by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.5. Hazard 5: Rainfall during the growing season

1.5.1. Indicator

Definition of the indicator: Total rainfall experienced during the growing season.

Relationship: Rain-fed cotton requires at least 500mm of rain throughout the growing season. A decrease in projected total rainfall will present a risk. Moreover, cotton does not favour waterlogged soils, therefore an increase in total rainfall in regions which already receive adequate rain, may present a risk to cotton.

1.5.2. Projected hazard for the 2040s

By the 2040s, some proportion of cotton growing regions are projected to experience less than the minimum required total rainfall during the growing season for rain-fed cotton crop to flourish (**Figure 8**). These regions span across the Middle East, including large proportions of cotton growing regions in Syria, Iraq, Iran and Afghanistan, cotton rowing regions in northern Africa including Egypt and northern Sudan, and cotton growing regions in Asia including Tajikistan, Kyrgyzstan, Uzbekistan, Turkmenistan, Pakistan and north-western China.

The wettest regions in the 2040s will be Venezuela and western Ecuador in South America, eastern Madagascar and western coast of Guinea in Africa, and Bangladesh, eastern India, southern Myanmar and Vietnam. Regions which are projected to experience the highest rainfall during the growing season include the majority of cotton growing regions in central South America, central Africa, and the majority of Southeast Asia.

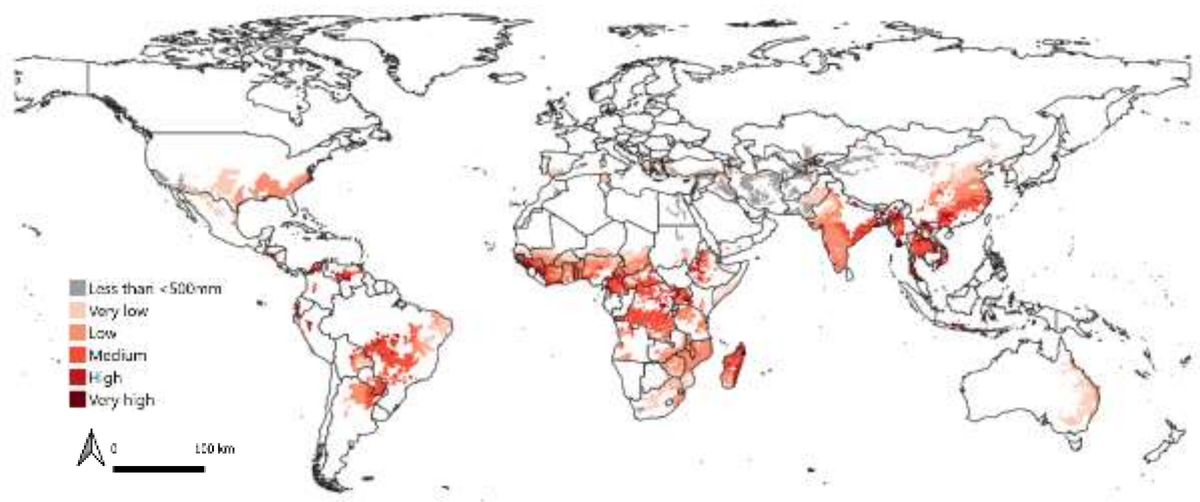

Figure 8: Projected total rainfall received during the growing season by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.5.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The greatest increase in total rainfall received during the growing season is projected to occur across regions which already received a significant volume of rain during the growing season (**Figure 9**). These regions are mainly located in southeast Asia across Myanmar, India, Thailand, Vietnam, and eastern cotton growing regions in China. Other hotspots of significant increase in rainfall are north-eastern Argentina, north-eastern cotton growing regions in the Democratic Republic of Congo, and Uganda.

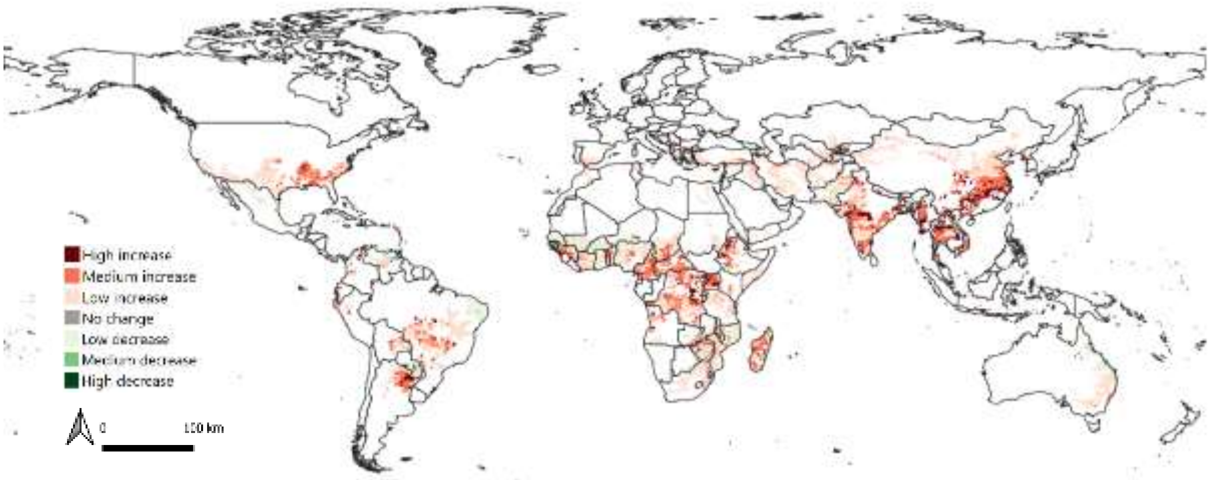

Figure 9: Projected change in total rainfall received during the growing season by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.6. Hazard 6: Extreme rainfall

1.6.1. Indicator

Definition of indicator: The percentage of total annual rainfall falling on 5% of the heaviest rainfall days. The indicator is used as a proxy for the intensity of extreme rainfall events.

Relationship: An increase in the intensity of extreme rainfall events increases the risk of flooding, waterlogging and damage to cotton fields. This is especially true in regions which experience extreme dry conditions, followed by extreme rainfall events. Depending on a number of factors, including rainfall intensity and soil structure and composition, dried-out soils can have a reduced capacity to absorb water, leading to increased runoff and risk of flooding.

1.6.2. Projected hazard for the 2040s

By the 2040s, the regions projected to experience the highest intensity of extreme rainfall events relative to other cotton growing regions are cotton growing regions along the Nile River in Egypt and northern Sudan (**Figure 10**). Other regions projected to experience a high intensity extreme rainfall events include the majority of cotton growing regions in Pakistan, northwest India, eastern Iraq, and southern Arizona in the US.

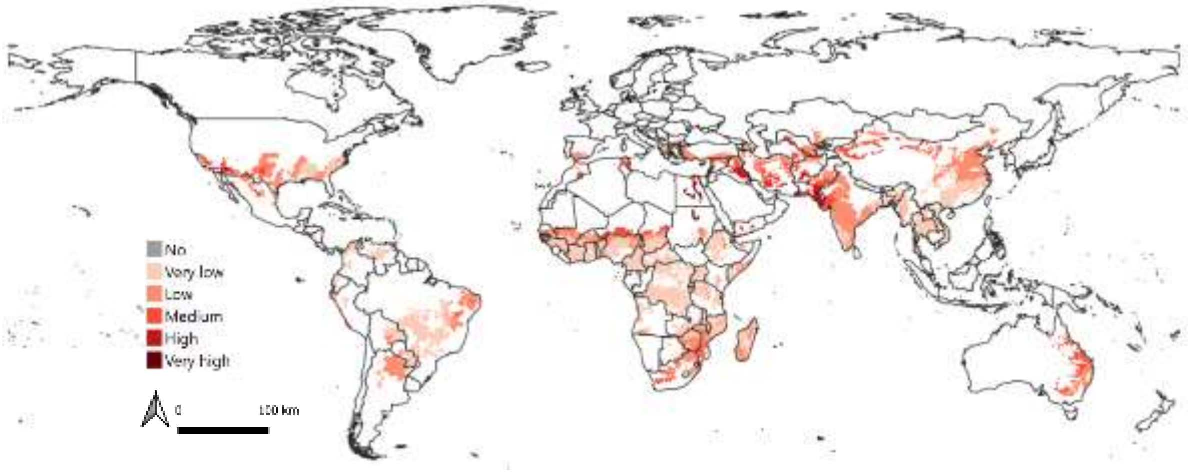

Figure 10: Projected percentage of total annual rainfall falling on 5% heaviest rainfall days by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.6.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

Extreme rainfall events are projected to become increasingly more intense by the 2040s across the majority of cotton growing regions (**Figure 11**). The greatest increase is projected for the regions in north-eastern Australia in the state of Queensland, with a "medium" increase projected for regions in south-central US, northern Argentina, southern Mali and Senegal, and regions in Zimbabwe and South Africa.

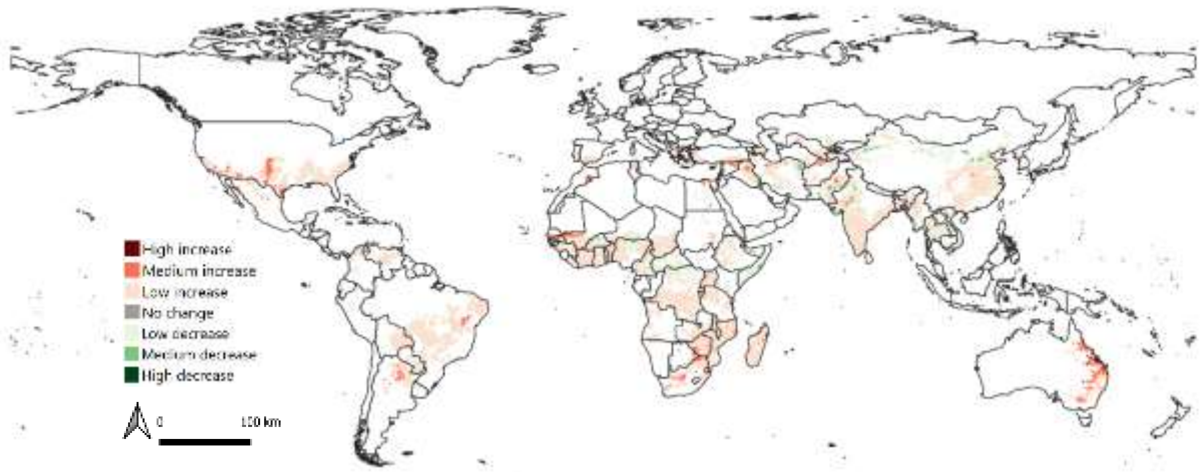

Figure 11: Projected change in percentage of total annual rainfall falling on 5% heaviest rainfall days by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.7. Hazard 7: Fluvial flooding

1.7.1. Indicator

Definition of the indicator: The projected fluvial flood depth during a 1-in-10 year flood event. This indicator is considered as flooding can cause widespread damage to agricultural crops.

Relationship: The greater the projected flood extent and depth, the greater the hazard to cotton growing regions.

1.7.2. Projected hazard for the 2040s

Numerous key cotton growing regions are located within close proximity to some of the world's main river systems and are projected to be exposed to flood risk by the 2040s (**Figure 12**). In Africa, the greatest flood depth during a 1 in 10 year flood event is projected across cotton growing regions located along the tributaries of Lake Kyoga in central Uganda, northern reaches of the Zambezi River in Mozambique, and along the Congo River in the Democratic Republic of Congo. In North and South America, the greatest flood depth occurs across cotton growing regions along the Mississippi River in the United States, tributaries of Lake Rio Yguazi in Paraguay, along Sao Francisco River in western Brazil, and along the majority of the length of the Orinoco river in Venezuela. In Asia, the greatest flood depth occurs across cotton growing regions located at the confluence between the Padma and Brahmaputra rivers in Bangladesh, along a significant length of both the Indus river in Pakistan and the Irrawaddy River in Myanmar, at southern reaches of the Mahi River and Tapi River in the western state of Gujarat and the Godavari river in the eastern state of Andhra Pradesh in India.

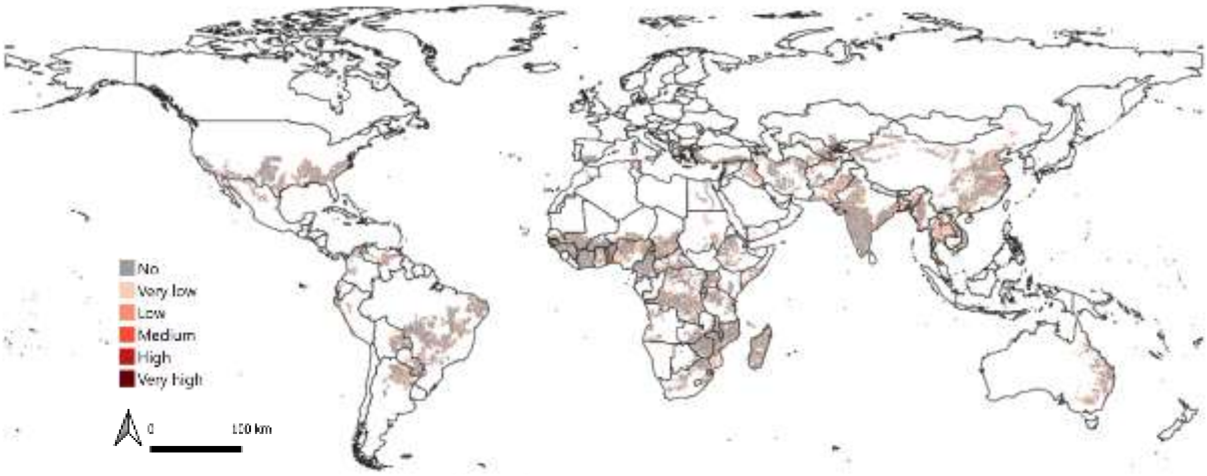

Figure 12: Projected fluvial flood risk during a 1 in 10 years by the 2040s across all cotton growing regions.

1.7.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

A relatively low increase in flood risk is projected across the majority of cotton growing regions located within close proximity to watercourses (**Figure 13**). The greatest increase in flood risk by the 2040s during a 1 in 10 year fluvial flood event is projected along São Francisco River in western Brazil, the Mahi River in western India, and the majority of the Irrawaddy River in Myanmar, along the Niger tributaries in Nigeria.

Some cotton growing regions are projected to experience a relatively high decrease in flood risk by the 2040s, including along the tributaries of Lake Volta in Ghana and along the tributaries of Lake Kossou in Cote d'Ivoire. Regions which are projected to experience a "low" decrease include regions across eastern China, northern Syria, southern Turkey, some regions in southern US, and central Brazil.

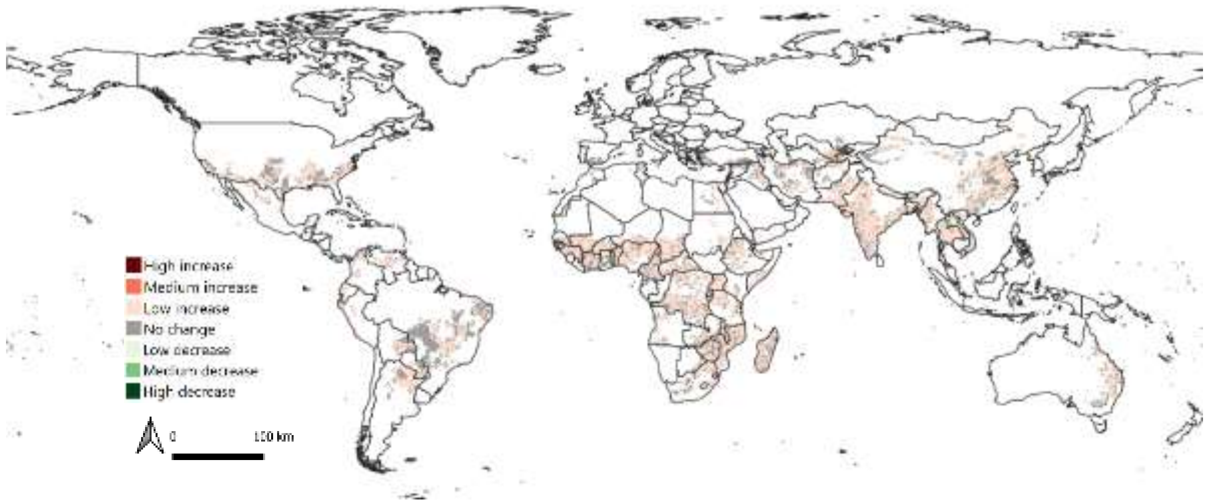

Figure 13: Projected change in fluvial flood risk during a 1 in 10 years by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.8. Hazard 8: Coastal flooding

1.8.1. Indicator

Definition of the indicator: The projected coastal flood depth during a 1-in-10 year return period. This indicator is used as coastal flooding can cause widespread damage to cotton crops located within close proximity to coastal regions.

Relationship: The greater the projected flood extent and depth, the greater the hazard to cotton growing regions.

1.8.2. Projected hazard for the 2040s

While the majority of cotton growing regions across the world are not located within close proximity to coastal regions, there are projected to be some hotspots exposed to coastal flooding by the 2040s (**Figure 14**). These include cotton growing region located along the coast in south-eastern Bangladesh, north-western region of India, south-western coast of Pakistan, northern coast of China, along the western coast of Myanmar, and along the eastern coast of Mozambique.

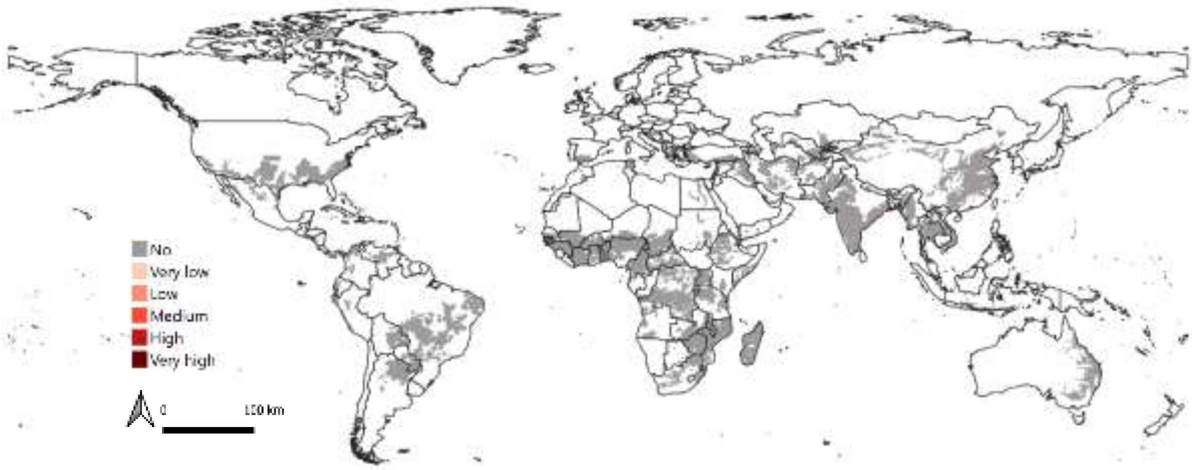

Figure 14: Projected coastal flood risk during a 1 in 10 years by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.8.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The cotton growing regions which are projected to experience the greatest increase in coastal flood risk by the 2040s are regions along the southern coastal region of the state of West Bengal in India, and along the central-eastern coast of China in the provinces of Shanghai, Jiangsu and Zhejiang (**Figure 15**).

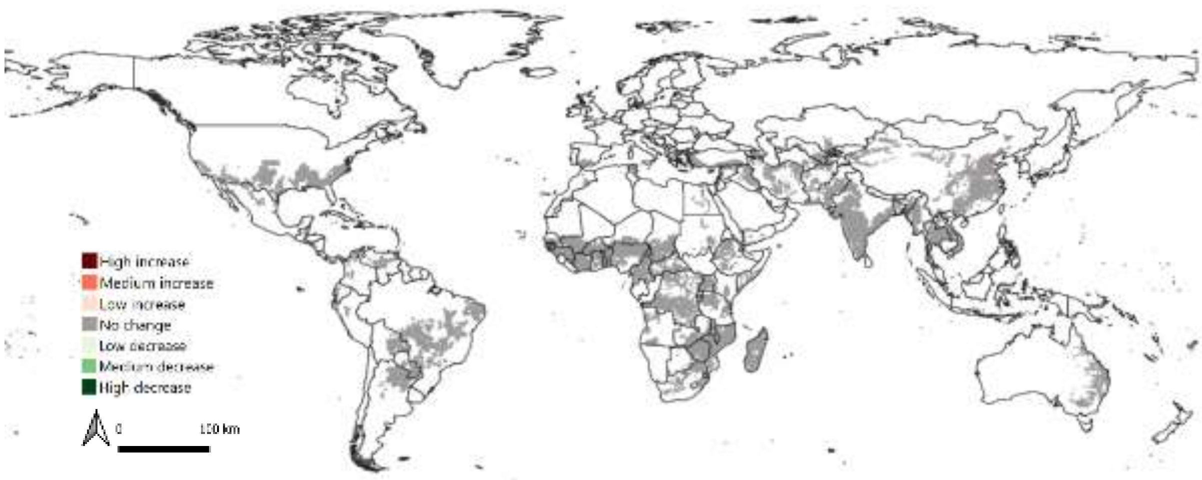

Figure 15: Projected change in coastal flood risk during a 1 in 10 years by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.9. Hazard 9: Wildfire

1.9.1. Indicator

Definition of the indicator: The projected number of days in a year when the climatic conditions for wildfire are correct, and that the risk of wildfire is high given sufficient fuel source if available.

Relationship: Wildfire poses a direct threat to agricultural crops, farming infrastructure and human health and safety, therefore the higher number of days when wildfire risk is "high" presents an increase in hazard risk to cotton.

1.9.2. Projected hazard for the 2040s

Wildfire risk is projected to be highest for cotton growing regions located within close proximity to the Tropic of Cancer, including southern cotton growing regions in Pakistan, southern Syria, central Iraq, the majority of cotton growing regions in Egypt, and some regions in southern cotton growing regions in the state of Arizona in the US (**Figure 16**). Wildfire risk is high along the latitude of 15°N in the northern regions of the sub-Saharan countries, especially cotton growing regions in central Chad, southern Niger and central Sudan, and across the majority of cotton growing regions in Yemen. The risk of wildfire is also relatively high across the majority of cotton growing regions in India, Brazil, cotton growing regions in southern Africa, and across the majority of cotton growing regions in the south-western states of the US.

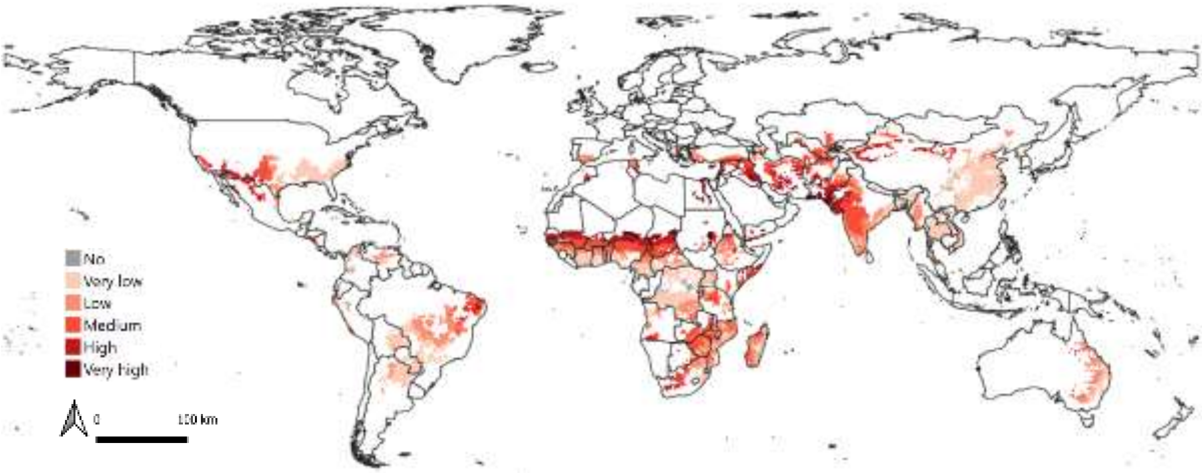

Figure 16: Projected number of days when the risk of wildfire is "High" by the 2040s across all cotton

1.9.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The majority of cotton growing regions are projected to experience an increase in the number of days when the climate conditions are correct for wildfire to occur given the availability of sufficient fuel source (**Figure 17**). The greatest increase is projected to occur across the entire northern cotton growing regions in China, across the western state of Xinjiang, Inner Mongolia and over to the north eastern states of Jiang and Heilongjiang. A high increase is also projected to occur across the majority of the cotton growing regions along the western coast of Peru.

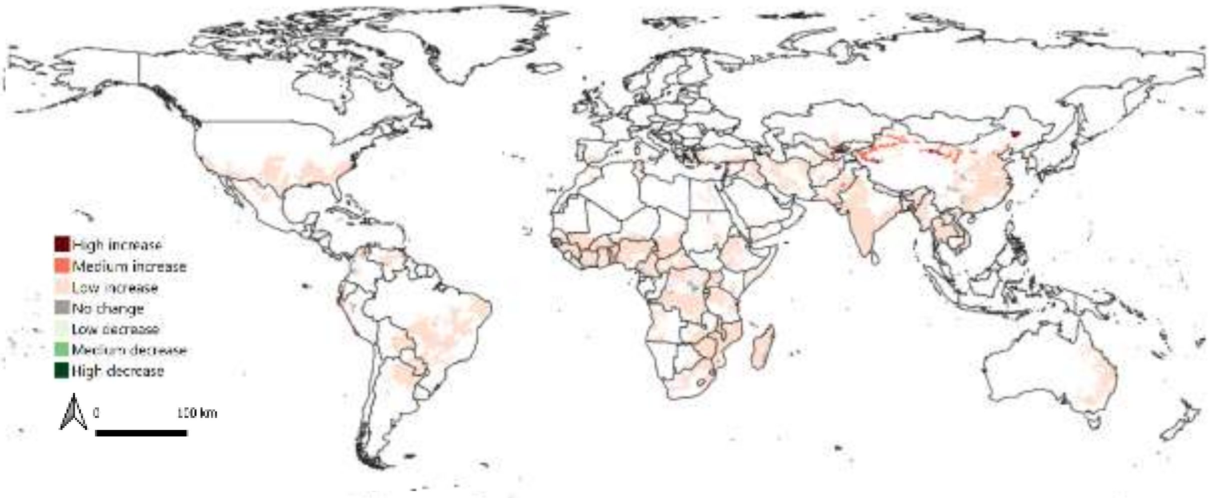

Figure 17: Change in projected number of days when the risk of wildfire is "Medium-High" by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.10. Hazard 10: Landslides

1.10.1. Indicator

Definition of the indicator: The number of days when the risk of precipitation-induced landslide is high.

Relationship: Landslides poses a direct threat to agricultural crops, thus a higher projected number of days when landslide risk is "high" presents an increased risk to cotton.

1.10.2. Projected hazard for the 2040s

Regions which are projected to be exposed to precipitation-induced landslide risk by the 2040s are cotton growing regions located in the Choke Mountains in northern Ethiopia, the northern regions of Vietnam, and north-eastern regions in India (**Figure 18**). Other regions which are projected to experience a high landslide risk include the Taurus Mountains over to the Armenian highlands in southern Turkey and the Zagros mountain range in northern Iraq, a hotspot in Nepal, Zhejiang province in eastern China, along the Andes mountain range between Peru and Ecuador, and across the majority of cotton grown areas of Haiti.

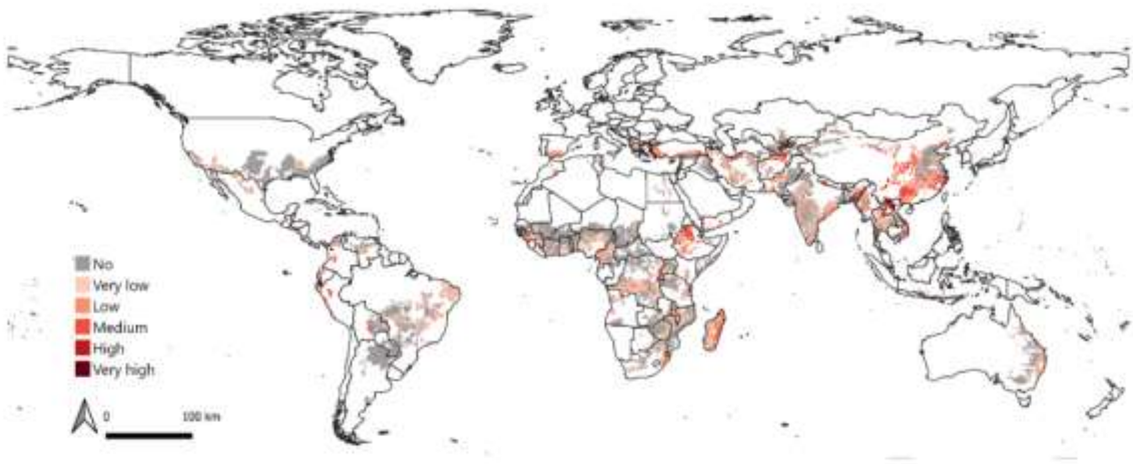

Figure 18: Projected number of days when the risk of precipitation-induced landslide is 'medium' or 'high' in a given year by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.10.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

A low increase in landslide risk is projected in the majority of the world's cotton growing regions by the 2040s. The greatest increase is projected for cotton growing regions located in north-western Ethiopia in the Choke Mountains, and in the Andes mountains between southern Ecuador and northern Peru (**Figure 19**).

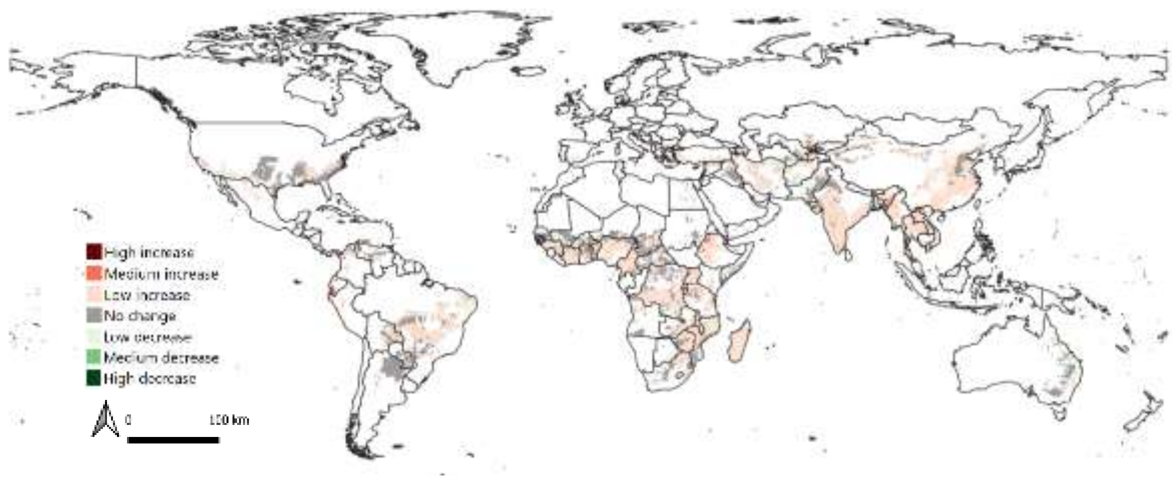

Figure 19: Change in projected number of days when the risk of precipitation-induced landslide is 'medium' or 'high' in a given year by the 2040s, relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing areas.

1.11. Hazard 11: Damaging wind speeds

1.11.1. Indicator

Definition of the indicator: The projected number of days when wind speeds exceeds 25 mph. This is based on the widely used Beaufort scale[2] to represent 'strong winds'.

Relationship: Strong winds pose a direct threat to cotton crops, thus a higher number of days when wind speeds exceed 25 mph presents an increased risk to cotton.

1.11.2. Projected hazard for the 2040s

Strong winds will be a high risk to cotton growing regions located along the eastern coast of Sudan, the eastern coast of the state of Rio Grande do Norte in Brazil, and along the northern tip of Madagascar (**Figure 20**). Other regions which are projected to experience strong winds include central United States, Somalia and South Africa.

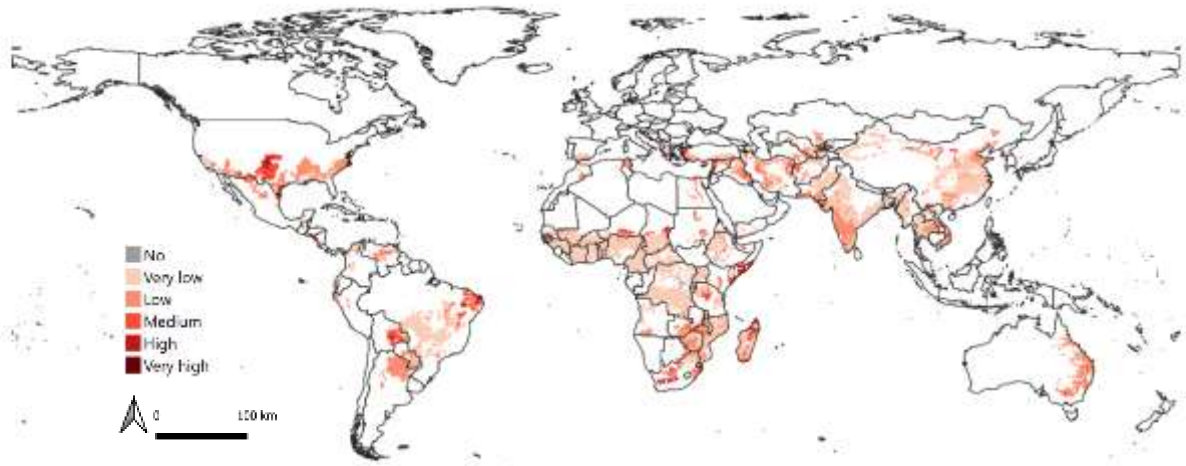

Figure 20: Projected number of days when wind speed exceeds 25mph by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions

1.11.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

Both an increase and a decrease in strong winds are projected across the world's cotton growing areas (**Figure 21**). There are two key regions which are projected to experience a significant increase in strong winds by the 2040s relative to present day, and these cotton growing regions are located along the north-western coast of Australia, in the central and northern regions in Madagascar and in eastern Brazil.

A few regions are projected to experience a decrease in exposure to strong winds including cotton growing regions in the southern state of Tamil Nadu in India, and two key locations in the United States in the states of South Carolina and Texas.

[2] *The Beaufort scale is a is an empirical measure for describing wind intensity based on observed sea conditions.*

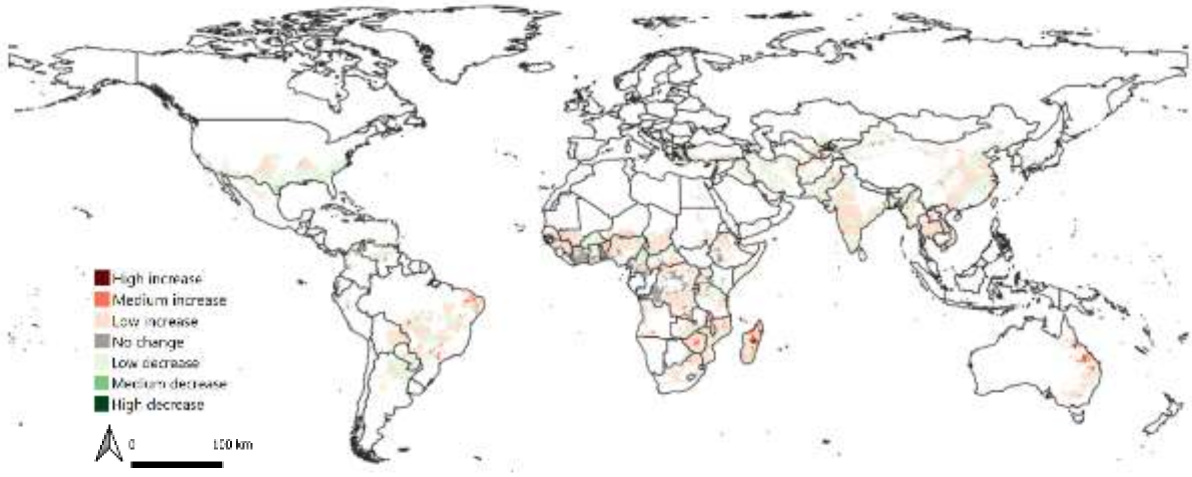

Figure 21: Change in projected number of days when wind speed exceeds 25mph by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions

1.12. Hazard 12: Storms

1.12.1. Indicator

Definition of the indicator: The projected number of days when wind speed exceeds 55 mph. This is based on the widely used Beaufort scale[3] to represent storms.

Relationship: Storms pose a direct threat to cotton crops, thus a higher number of days when wind speeds exceed 55 mph presents an increase in hazard risk to cotton.

1.12.2. Projected hazard for the 2040s

The majority of cotton growing regions do not experience storms (**Figure 22**). Nonetheless, there are key hotspots which experience a significant exposure to storms, and these are cotton growing regions located along the western coast of Turkey in the Aegean Sea, and in the Zagros Mountains in Iran. Other regions include cotton growing area in the states of Texas, Oklahoma and Kansas in the United States, in the south-eastern Amazonian region of Bolivia, southern Spain, eastern Sudan, and along the eastern coast of China in the provinces of Zhejiang and Fujian.

[3] *The Beaufort scale is a is an empirical measure for describing wind intensity based on observed sea conditions.*

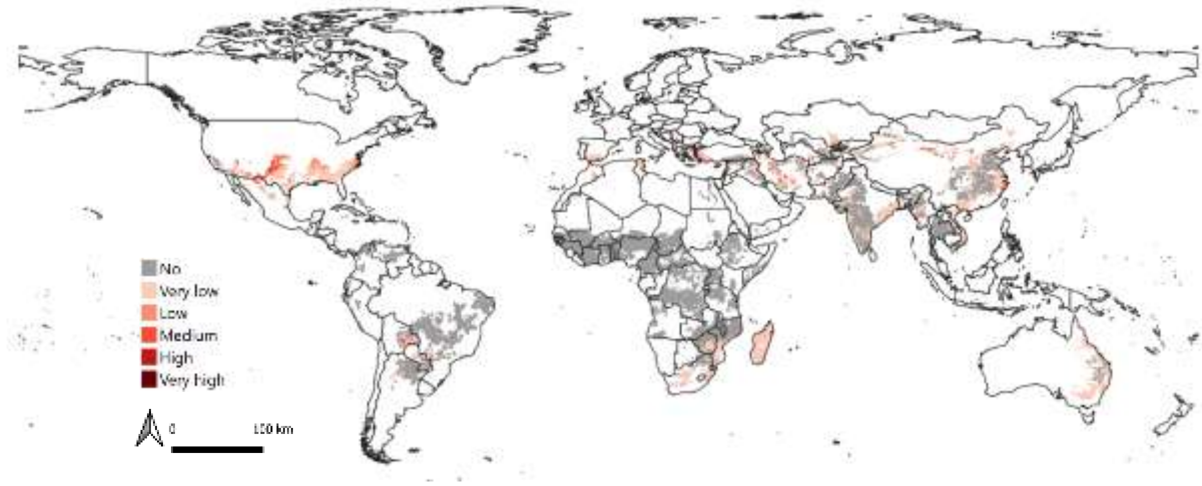

Figure 22: Projected number of days when wind speed exceeds 55mph by the 2040s across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

1.12.3. Magnitude of change in the projected hazard for the 2040s relative to present day hazard

The magnitude of change for most regions exposed to storms is relatively low (**Figure 23**). There is only one region which is projected to experience a significant increase in storms by the 2040s relative to present day, and this is a cotton growing region located between eastern Afghanistan and western Iran. Cotton growing regions across the southern states of Texas, Oklahoma and Kansas in the United States are also projected to experience an increase in exposure to storms.

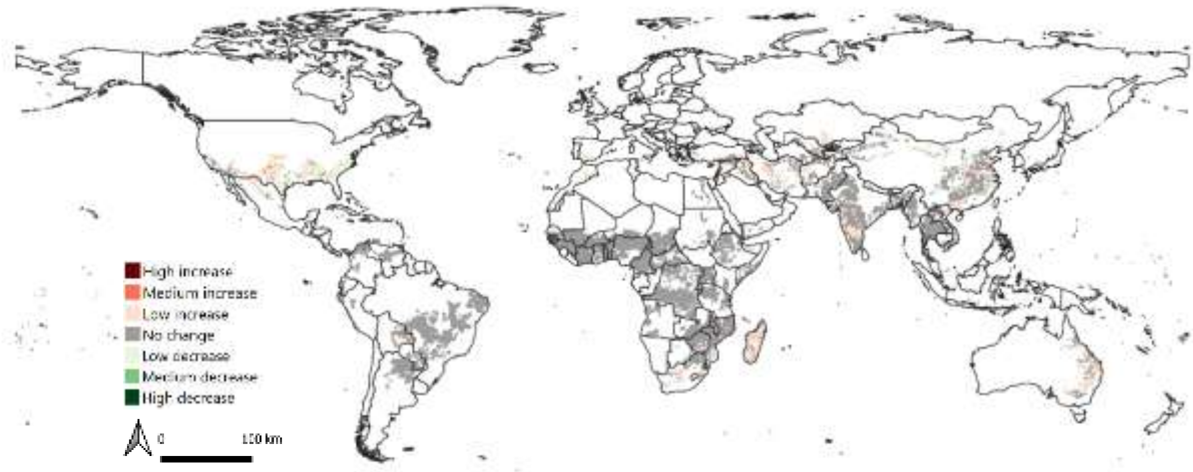

Figure 23: Change in projected number of days when wind speed exceeds 55mph by the 2040s relative to present day (2000-2019) across all cotton growing regions. The measure is relative to measures against other cotton growing regions.

Part C: Next steps

How should this report be used?

The Global Analysis, and the detailed India Analysis, were both generated by Cotton 2040 in response to the lack of comprehensive, readily available information about how the climate crisis is likely to impact cotton production, its supply chain, and the nature of the industry over the coming decades.

The reports and supporting resources are aimed at apparel brands and retailers, cotton producers or those working with them, sustainable cotton standards and industry associations, the climate finance community, civil society organisations working on climate justice and adaptation, and other actors across the cotton value chain.

The information presented in this report is designed to help users identify the relative level of physical climate hazards projected in the 2040s across the world's cotton growing regions. Numerous climate hazard indicators are amalgamated into a single climate risk score to enable the report user to identify the cotton growing region at greatest overall risk from climate change. Secondly users can obtain information on the main hazards that are contributing to the climate risk score, i.e. temperature-related variables, water-related variables, and so forth.

In exploring these findings, individuals and organisations should consider the question:

"How can I, as a stakeholder in the cotton value chain, take action to help address climate risks and work towards increasing climate resilience in key cotton growing regions?"

Addressing this question forms the core objective of the Cotton 2040 Climate Adaptation workstream and its work through 2021-22 and beyond. The focus will be on supporting the sector to further engage with the findings of this technical evidence-based global report; deepen their understanding of the potential implications for individual organisations and the cotton industry; and – critically – create cross-sector dialogue to identify and act collectively on systemic solutions. We hope you will join us!

To access the reports, the Climate Risk Explorer tool and supporting resources visit www.acclimatise.uk.com/collaborations/cotton-2040/. For more information, please contact: Erin.Owain@willistowerswatson.com.

To learn more and explore how your organisation can help create a resilient cotton sector, please contact Hannah Cunneen at h.cunneen@forumforthefuture.org.

To find out more about Cotton 2040 visit www.forumforthefuture.org/cotton2040.

Glossary

Baseline scenario- Scenario without the project, or scenario that is based on the assumption that no mitigation policies or measures will be implemented beyond those that are already in force and/or are legislated or planned to be adopted. Baseline scenarios are not intended to be predictions of the future, but rather counterfactual constructions that can serve to highlight the level of emissions that would occur without further effort. “Baseline Scenario” is used synonymously with “Reference Scenario”, but also sometimes with “Business-as-Usual (BAU) Scenario” although the use of the term BAU has fallen out of favour due to uncertainties in very long-term projections.[i]

Climate change- A change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods.[ii]

Climate change adaptation- Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities.[iii]

Climate variability- Climate variability refers to variations in the climate on all spatial and temporal scales beyond that of individual weather events. Variability may be due to natural internal processes within the climate system (internal variability), or to variations in natural or anthropogenic external forcing (external variability).[iv] The term is often used to denote deviations of climatic statistics over a given period of time (e.g. a month, season or year) when compared to long-term statistics for the same calendar period. Climate variability is measured by these deviations, which are usually termed anomalies.[v]

Extreme weather event- Refers to weather phenomena that are at the extremes of the historical distribution and are rare for a particular place and/or time, especially severe or unseasonal weather. Such extremes include flooding, hurricanes, and high winds, and heat waves.[vi] When a pattern of extreme weather persists for some time, such as a season, it may be classed as an extreme climate event, especially if it yields an average or total that is itself extreme (e.g., drought or heavy rainfall over a season).[vii]

Hazard- The potential occurrence of a natural or human-induced physical event or trend or physical impact that may cause loss of life, injury, or other health impacts, as well as damage and loss to property, infrastructure, livelihoods, service provision, ecosystems, and environmental resources. In the context of climate change, the term hazard usually refers to climate-related physical events or trends or their physical impacts.[viii]

Representative concentration pathways (RCPs)- Understanding the relationship between GHG emissions of today and its long-term impacts over the next years or decades requires standardised basis. RCPs are scenarios that describe alternative trajectories for CO_2 emissions and its resulting concentration in the atmosphere from 2000 to 2100. RCPs provide common standard scenarios for climate researchers and modellers to work on. Projected change in temperature by 2081-2100 relative to 1850-2100 for +1.6°C for RCP 2.6, +2.4°C RCP 4.5, +2.8°C for RCP 6.0. and +4.3°C for RCP 8.5.

Resilience- The capacity of social, economic, and environmental systems to cope with climate change induced hazardous events or trend or disturbance, responding or reorganizing in ways that maintain their essential function, identity and structure, while also maintaining the capacity for adaptation, learning and transformation.[ix]

Risk- The potential for consequences where something of value is at stake and where the outcome is uncertain, recognising the diversity of values. Risk is often represented as probability of occurrence of hazardous events or trends multiplied by the impacts if these events or trends occur. Risk results from the interaction of vulnerability, exposure and hazard. The Intergovernmental Panel on Climate Change (IPCC) primarily use the term risk to primarily refer to the physical risks of climate change impacts.[x]

Acronyms

CVC – Cotton Value Chain

EGDD – Effective Growing Degree Days

GCM – Global Circulation Models

GCP – Global Climate Projections

GDP – Gross Domestic Product

IPCC – Intergovernmental Panel on Climate Change

RCP – Representative Concentration Pathway

UNFCCC – United Nations Framework Convention on Climate Change

Appendix 1: Methodology

This study assesses physical climate risks to cotton growing areas globally. This chapter presents the methodology used in this study.

Step 1: Identifying the climate-related data sources and types

The most suitable, reliable and credible sources were used to harvest the climate-related datasets that underpin the indicators utilised in this study. Specifically, datasets were obtained from internationally recognised data sources, including the European Centre for Medium-Range Weather Forecasts (ECMWF), the Coupled Model Intercomparison Project Phase 5 (CMIP5), the World Resource Institute (WRI), and the National Aeronautics and Space Administration (NASA).

The types of datasets harvested from such institutions are described as follows:

- **Reanalysis:** Reanalysis is a scientific methodology for developing a comprehensive record of weather and climate variables. It combines large volumes of observed data from weather stations and remote sensors with high-resolution numerical weather models. Reanalysis is the closest dataset available to pure observed data on a global scale. It also covers a wide range of climate variables at time scales and spatial resolutions relevant to the analyses required for this project.
- **Global climate projections (GCP):** Climate projections obtained from GCMs. GCMs are coupled atmospheric-oceanic models that account for a wide range of physical processes. Due to their global coverage, GCMs have coarser spatial resolutions than downscaled climate projections, and are typically in the order of 100 km resolution.
- **Climate-related hazard datasets from other internationally recognised sources**: Climate-related hazards not present in reanalysis or climate projections**.** These include the landslide susceptibility provided by NASA's Landslide Hazard Assessment for Situational Awareness (LHASA) and the coastal and riverine flooding hazard datasets from the World Resource Institute (WRI).

The suitability of the different types of datasets is taken into consideration for each required climate-related variable. Reanalysis data is used to calculate the most recent observed local climatology (2000-2019) while its high spatial resolution provides the foundation on which to simulate future climatologies.

Given the uncertainty in GCPs, it is important to base the calculation of future climatologies on a reasonable number of GCMs, as this provides a sensible confidence range in light of any possible uncertainty. Additionally, GCPs can be post processed to reduce their inherent bias (bias-correction) and to infer higher spatial resolution climate projections (known as downscaled climate projections). In this project, we used reanalysis data in combination with GCPs to obtain statistically downscaled climate projections. Statistical downscaling makes use of statistical relationships between local observed climate variables (order of ~1-30 km spatial resolution) and larger-scale climate patterns (orders of 100s km spatial resolution). The derived statistical relationships are in turn applied to the large-scale projections data from GCMs to infer local-scale projections at a higher resolution.

Table 1 summarises the data sources harvested and type of datasets used for each climate-related variable and the associated indicators.

Table 1. Summary of datasets and sources used in the analysis

Climate-related variable	Dataset type for historical analysis	Data source for historical analysis	Dataset type for future projections analysis	Data sources for future projections analysis	Climate-related Indicators
Temperature, daily mean	Reanalysis	ECMWF	Reanalysis, GCP	ECMWF, CMIP5	Effective growing degree days.
Temperature, daily max	Reanalysis	ECMWF	Reanalysis, GCP	ECMWF, CMIP5	Days above maximum threshold for growing cotton (>40°C).
Total precipitation, daily	Reanalysis	ECMWF	Reanalysis, GCP	ECMWF, CMIP5	Total rainfall during GS. Extreme precipitation: Characterised as the percentage of total annual rainfall falling on 5% heaviest rainfall days. This indicator is a good proxy for pluvial flood. Meteorological drought: Characterised as the number of days in which the 3-month Standardised Precipitation Index (SPI) is below – 1.5 (severe drought). Hydrological drought: Characterised as the number of days in which the 18-month Standardised Precipitation Index (SPI) is below – 1.5 (severe drought).
Wind gust, daily	Reanalysis	ECMWF	Reanalysis, GCP	ECMWF, CMIP5	Damaging wind speeds: Number of days with wind gusts above 25 mph. Storm winds: Number of days with wind gusts above 55 mph.
Fluvial flooding	Climate hazard dataset	WRI Aqueduct	Climate hazard dataset	WRI Aqueduct	1 in 10 year flood extent

Coastal flooding	Climate hazard dataset	WRI Aqueduct	Climate hazard dataset	WRI Aqueduct	1 in 100 year flood extent
Landslide hazard (rainfall-induced)	Climate hazard dataset, Reanalysis	NASA, ECMWF	Climate hazard dataset, Reanalysis, GCP	NASA, ECMWF, CMIP5	Days with rainfall-induced landslide hazard medium or high.
Wildfires (Fire Weather Index (FWI))	Reanalysis	ECMWF	Reanalysis, GCP	ECMWF, CMIP5	Weather conditions for wildfire are considered very dangerous: Represented as the number of days with FWI above 20.

Step 2: Defining inputs and boundary conditions

Climatologies and time horizons

Observed climate exhibits natural year-to-year, as well as decade-to-decade variability, such as the El Niño Southern Oscillation (ENSO) or the Pacific Decadal Oscillation (PDO). Climate models, being representations of the earth system, also model natural climate variability.

The term climate, as defined by the World Meteorological Organization, refers to "average weather" over multiple decades. Time horizons of interest were discussed and agreed with the Working Group[4]. For the latest climate projections, a 20-year period, centred around any one future time horizon of interest, is considered appropriate for this analysis. The aim is to smooth out single or multi-year modelling anomalies where under/over estimations can be present and to account for decade-to-decade climate variability. The analysis is therefore centred on the 2040s, analysing across a 20-year climatology from 2031 to 2050.

The Working Group also have an interest in the relative change between present day and 2040s. Based on the most recent available observed data, present-day has been defined as a 20-year climatology from 2000 to 2019 and this forms the baseline use in the study. The data sources for present day are derived from the ERA5 and ERA5-Land reanalysis data sets (both part of the ECMWF dataset[5]). To calculate the relative change, the projections for the 2040s are subtracted from the present day conditions.

To summarise, the climatological analysis in this project is therefore undertaken for the following longer-term observed and future climatologies:

- **Baseline/Present day condition:** 2000-2019:
- **Future projections:** 2031-2050: centred on the 2040s.

[4] *The Working Group consist of selected stakeholders with expertise in various stages of the cotton value chain. The Working Group have been consulted at various stages of the project.*

[5] *ECMWF is the European Centre for Medium-Range Weather Forecasts. https://www.ecmwf.int/en/about*

Statistical downscaling

Rather than directly obtaining modelled future absolute values from GCPs, the statistical downscaling approach helps ensure that any inherent modelling bias is corrected for and that the data spatial resolution is enhanced. The methodology for statistical downscaling consists of:

1. For each GCM, the relative changes between the cumulative distribution functions (CDF) of future and baseline periods are calculated for each percentile.
2. These relative changes are applied to the CDF of the present day reanalysis in order to project it into the future. In this study, the dataset ERA5 (from ECMWF) is employed with a global spatial resolution of 25 x 25 km.
3. The newly calculate CDF, which represents the future time horizon with the same spatial resolution as the original reanalysis dataset, is reverted back to a time series.
4. These steps are repeated for each climate variable.

For example, **Figure 23** shows the statistical downscaling methodology applied to calculate the projected absolute values of the daily mean temperature for Banas Kantha in the 2040s. Significant differences in the changes between future and present day GCM's CDFs can be noted across the distribution. Especially notable is the convergence of both CDFs in the tail end temperatures (coldest and warmer). Therefore, it is essential to account for the different changes across the percentiles of the distribution, rather than simplistically applying one change value to the whole distribution when obtaining the projected future value (solid red line).

This sophisticated methodology is referred to as parametric quantile mapping reordering[6], and is one of the most widely used approaches for statistical downscaling of daily data. This methodology is utilised in this study.

[6] *https://doi.org/10.5194/hess-20-1483-2016*

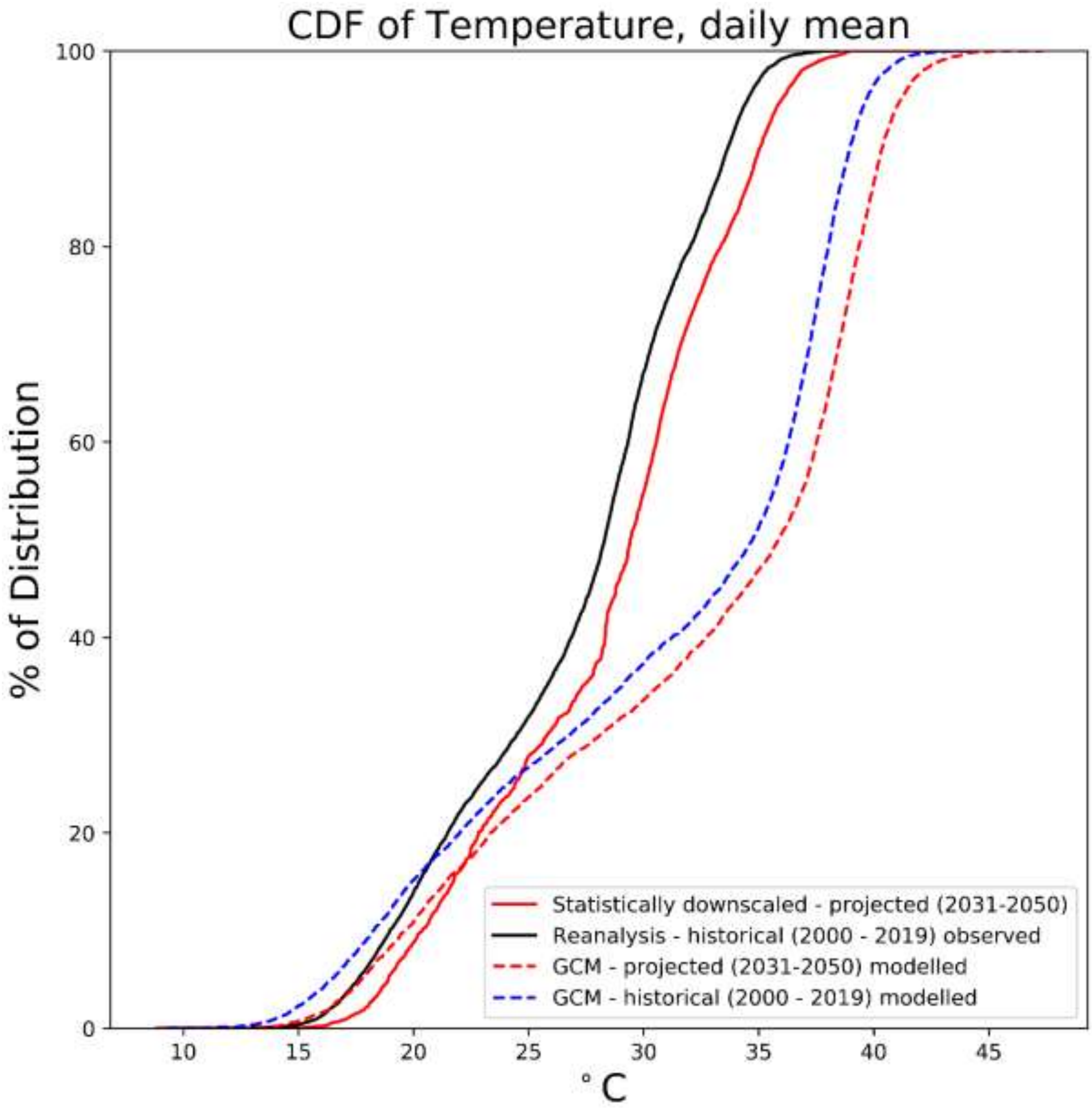

Figure 23. Example of the quantile mapping methodology. Cumulative Distribution Functions (°C) of daily mean temperature at Banas Kantha (Latitude = 24° 18' 39"N; Longitude = 71° 47' 12"E). Present day 2000–2019 derived from ERA5 Reanalysis data (solid black line). Modelled projected 2031-2050 for RCP8.5 and modelled historic values are shown for one GCM (ACCESS1-3) as dashed lines. The relative changes of the GCM for each percentile of the distribution are used to calculate the final projected absolute values for 2031-2050 (solid red line). The newly calculated CDF is reversed back into the original data in order to obtain a time series of downscaled values. Source: WTW, 2020

Indicators and percentiles calculations

Climate-related indicators based on each of the climate-related variables are calculated for present day and the 2040s, computing against defined thresholds (such as EGDD, which is the sum of "°C" during the growing season period).

The first step in the analysis is to statistically downscale the climate-related variables of each GCM as described in the previous section. Subsequently, the newly downscaled time series are employed to obtain the projected climate-related indicators for each GCM. The mean of the ensemble model distribution (also referred to as the 50th percentile, or P50) is used. Representative Concentration Pathway (RCP) selection

In 2014, the IPCC published its fifth assessment report (AR5). AR5 provides a comprehensive assessment of literature on the three inter-related aspects of climate change science: the physical science; impacts, vulnerability and adaptation; and mitigation. The literature underpinning AR5 is, to a large extent, associated with climate projections from the 5th phase of the Coupled Model Inter-comparison Project (CMIP5), for the first time using RCPs. RCPs describe the evolution of future atmospheric greenhouse gas (GHG) concentrations without any assumptions on mitigation actions, thus RCPs are possible future GHG emissions and concentration scenarios that give rise to a given radiative forcing.

Four RCPs (RCP8.5, RCP6.0, RCP4.5 and RCP2.6) have been widely used in climate modelling as well as adaptation and mitigation analyses. Each RCP number represents the projected radiative forcing at 2100, for example, 2.6Wm^2 of radiative forcing by 2100 is represented by RCP2.6.

In addition, all RCPs show a broadly similar warming pathway up to mid to late 2030s, with no significant difference. As shown in **Figure 24**, RCPs begin to diverge after 2030s. Current warming trends exceed that projected by all RCPs except RCP8.5.

For this study, the highest emission scenario available from the IPCC has been selected, namely the RCP8.5, as this will show the significant challenges that the sector could face in the future.

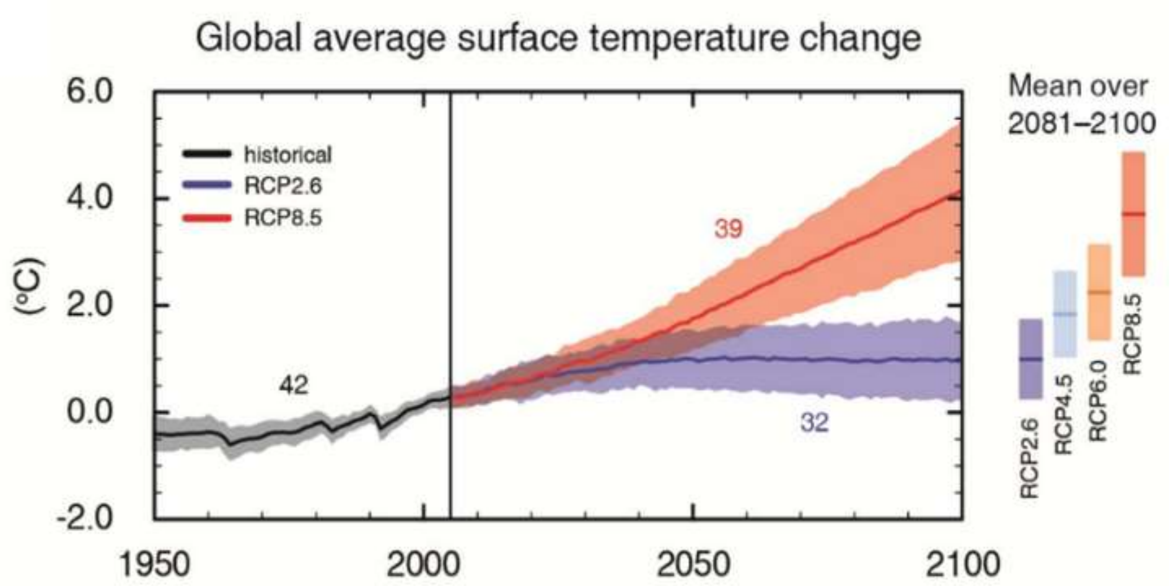

Figure 24: Multi-model simulated change in global annual mean surface temperature from 1950 to 2100 relative to 1986–2005.

Uncertainties

Uncertainty in climate information stems from a number of key areas including:

- Natural climate variability resulting from natural processes within the climate system which cause changes in climate over relatively short time scales.
- Future emissions of greenhouse gases arising from uncertainty over the scale of future global emissions of greenhouse gases.
- Modelling uncertainty arising from incomplete understanding of earth system processes and incomplete representation of these processes in climate models.

It is important to recognise these uncertainties in terms of this study and the methods deployed to reduce uncertainties as far as possible.

Step 3: Identifying the indicators and thresholds

An exhaustive literature review was carried out in order to determine cotton's main climate sensitivities. Specific climate thresholds, such as optimum temperature range and minimum rainfall during the growing seasons, was extracted from the literature for each of the four main cotton species, namely *Gossypium hirsutum* (upland cotton), *Gossypium barbadense* (extra long staple cotton), *Gossypium arboreum* (tree cotton) and *Gossypium herbaceum* (Levant cotton). Initially, thresholds were extracted for each of the crop development stages, namely 'Germination and Emergence', 'Leaf Area and Canopy Development', 'Flowering and Boll Development' and 'Maturation', however this proved to be too extensive for the scope of the work. Climate thresholds were extracted from credible and reliable sources.

Following a thorough literature review and following an 'information request' consultation with the Working Group members, significant gaps were missing in the climate information for the species *G. barbadense, G. arboreum* and *G. herbaceum*. Further consultation with renowned cotton experts recommended that the study solely concentrates on the predominant cotton species, *G. hirsutum*, which represents ~90% of global cotton production.

The literature review revealed that *G. hirsutum* is sensitive to both heat stress and water stress throughout the crop developed, therefore the climate variables 'temperature' and 'precipitation' formed the basis on many of the climate indicators considered in this analysis.

Specific thresholds applied to indicators in this study include:

- Optimum temperature range of 15°C to 30°C is used to determine the Effective Growing Degree Days (EGDD);
- A temperature threshold of 40°C is used to determine the maximum temperature for crop development; and
- A threshold of at least 500mm is used to define the total rainfall required throughout the growing period for rain-fed cotton.

Furthermore, the literature review reveals that cotton is also sensitive to extreme weather events and hazards including high wind speeds, fluvial and coastal flooding, wildfire and landslides, therefore these indicators have also been considered in the analysis.

See **Section 1.2** for a full description of cotton's climate sensitivities at different stages of crop development.

Step 4: Cotton data

Data on cotton production was derived from International Food Policy Research Institute.[xi] Data is available on a global coverage and relatively high resolution of 10km x 10km. Data is available for area, production and yield, and is available for irrigated, rainfed and total cotton.

Step 5: Building the index

Each individual component of the analysis was constructed separately, and a Geographical Information System (GIS) database was setup to act as a platform to merge the components. The GIS data layers are subsequently used as an input to an index model, allowing like-for-like comparisons of locational scores to be undertaken as an indicator of their overall impact of cotton production.

Appendix 2: Metadata table

	Type	Indicator	Definition *[Absolute and delta change to be considered when possible]*	Rationale	Data source
1	Temperature	**Effective Growing Degree Days (EGDD) - Absolute** *(Length of the growing season)*	Projected number of EGDD (<30°C) during growing season. The growing season begins when daily average temperatures first exceed >15°C for >6 consecutive days and ends when daily average temperatures go below 15°C for >6 consecutive days.[i]	According to the FAO, the optimal temperature range for optimal growth of cotton is between 15-30°C. This range determines the threshold for the growing season. Increases in the length of the growing season provides an opportunity for cotton cultivation. However, a negative change in growing season length, possibly due to an exceedance of temperature above optimal threshold of 30°C, will present a risk to cotton cultivation.	Reanalysis: ERA5 Projection: CMIP5
2		**Maximum threshold for cotton growing**	Projected number of days when temperature exceeds >40°C	Cotton crop is negatively impacted if temperature increases above 40°C. A projected increase in times the temperature exceeds this threshold, will present a risk to cotton crop.	Reanalysis: ERA5 Projection: CMIP5
3	Water	**Total growing season rainfall**	Projected precipitation >500mm during growing season (rainfed cotton growing regions).	Cotton requires total rainfall throughout the growing season in excess of >500mm. If total rainfall is <500mm, the crop can be negatively impacted.	Reanalysis: ERA5 Projection: CMIP5
4		**Extreme precipitation (pluvial flood)**	Percentage of total annual rainfall falling on 5% heaviest rainfall days	Extreme rainfall events can lead to waterlogged conditions, which may in turn inundate cotton plantations. An Increase in intensity and frequency of extreme rainfall events increases the risk of waterlogging and crop damage.	Reanalysis: ERA5 Projection: CMIP5

5		**Meteorological drought**	Projected annual average 3-month standard precipitation index (SPI)	The Standardized Precipitation Index (SPI) is a drought index based on precipitation and calculated as the average of the previous 3 month for each month (SPI12). An SPI >1.5 is classified as "very wet".	Reanalysis: ERA5 Projection: CMIP5
6		**Hydrological drought**	Projected annual average 18-month standard precipitation index (SPI). SPI accumulation periods over 12-48 months can be used as a proxy for groundwater recharge (where lower recharge suggests diminishing availability).[ii]	The Standardized Precipitation Index (SPI) is a drought index based on precipitation and calculated as the average of the last 18 month for each month (SPI18). An SPI >1.5 is classified as "very wet".	Reanalysis: ERA5 Projection: CMIP5
7		**Fluvial flood**	Projected in 1-in-10 year flood extent (binary indicator).	Extreme rainfall events which lead to flooding can cause widespread damage to agricultural crops. For example, in 2010, flooding caused significant damage to cotton production across Pakistan, causing a significant reduction in the crop area for cotton production. The IPCC projects that climate change will increase the intensity and frequency of extreme weather events across India. The higher the percentage of cotton growing areas located in fluvial flood zones, the higher the vulnerability.	Reanalysis: https://data.jrc.ec.europa.eu/collection/id-0054 / WRI Projection: https://data.jrc.ec.europa.eu/collection/id-0054 / WRI
8	**Coastal**	**Coastal flooding (Sea level rise and storm surge)**	Projected area inundated relative to baseline for a return period of 100 years at 1km resolution.	Sea level rise is projected to continue increasing over the next century, exposing coastal cotton growing regions to coastal flooding and storm surges. The higher the percentage of cotton growing areas located in coastal flood zones, the higher the vulnerability.	Reanalysis: N/A Projection: WRI
9	**Wind**	**Strong wind**	Projected wind gust above baseline wind speeds. We use 25 mph -- based on Beaufort scale	Combines both wind and cyclone. No exact threshold was identified, although FAO states that strong winds can affect the delicate young seedlings as wind can blow fibre away from opened bolls and soil the fibre with dust under the correct conditions.	Reanalysis: ERA5 Projection: Wind gust (from ERA5)

10	**Wind**	**Storms**	Projected wind gust above baseline wind speeds. We use 55 mph -- based on Beaufort scale	Combines both wind and cyclones. Although there is not a precise threshold, FAO states that strong winds can affect the delicate young seedlings as wind can blow fibre away from opened bolls and soil the fibre with dust under the correct conditions.	Reanalysis: ERA5 Projection: Wind gust (from ERA5)
11	**Wildfire**	**Wildfire**	Projected number of days when fire weather index is greater than 20 – "Medium-high" and projected number of days when fire weather index is greater than 30 – "High"	Wildfires cause significant damage to agricultural crops. This literature review did not find an example of a study which has previously considered the impacts of changes in wildfire on cotton cultivation. However past events clearly demonstrate that wildfires are a risk to cotton such as the recent Australian wildfires. The IPCC projects that climate change will increase the intensity and frequency of wildfires across the world. The higher the percentage of cotton growing areas located in wildfire zones, the higher the vulnerability.	Reanalysis: www.globalfiredata.org Projection: Fire Weather Index (e.g. to use projected no. fire weather days)
12	**Landslide**	**Landslides**	Projected precipitation induced landslides.	Landslides cause significant damage to agricultural crops. The IPCC projects that climate change will increase the intensity and frequency of landslides across regions which are projected to experience an increase in rainfall. The higher the percentage of cotton growing areas located in landslide zones, the higher the vulnerability.	Reanalysis: ERA5 Projection: CMIP5

Appendix 3: References

Part A. Background, context and research objectives

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