A REVIEW OF SUSTAINABLE AGRICULTURE RESEARCH IN GLOBAL COTTON CROPPING SYSTEMS

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ABSTRACT

Cotton is the most important fiber crop in the world for the fashion industry, national economies, and millions of farmers worldwide. Severe soil degradation as a result of long-term use of intensive agricultural practices is a serious challenge to future production as well as meeting global climate and nature targets. Fashion companies are responding to the realization that their dependence on soil and agriculture for raw materials is under threat. With total cotton production projected to grow, it is critical that cotton cropping systems are carefully managed to preserve the health and productivity of land, sustain livelihoods of growers and value chain actors, and build resilient supply chains in the face of climate change. This paper presents a review of soil conservation research in cotton-based systems, with the objective of informing the development of site-specific approaches to sustainable agriculture and regenerative land management.

BIOGRAPHICAL SKETCH

Debra Guo pursued the MPS in Soil & Crop Sciences at Cornell University during 2021 to 2022. Before coming to Cornell, she was Head of Sustainability at Stella McCartney, a leader in sustainable and cruelty-free luxury fashion. Debra is interested in combining evidence-based soil conservation frameworks, farmer-centered approaches, and her industry experience to build regenerative fashion supply chains from the ground up that restore ecosystem health and improve rural livelihoods. She holds a Bachelor of Arts in Geography from the University of Oxford and a Master of Science in Environment and Development from the London School of Economics and Political Science.

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LIST OF ABBREVIATIONS

ABRAPA	Associação Brasileira dos Produtores de Algodão
AM	Arbuscular mycorrhizal
B	Biological
C	Carbon
CA	Conservation Agriculture
CC	Cover crops
CCAFS	Climate Change, Agriculture and Food Security
Ch	Chemical
CIMMYT	International Maize and Wheat Improvement Center
CmiA	Cotton made in Africa
CR	Crop rotation
CSA	Climate-smart Agriculture
CEC	Cation exchange capacity
CO_2	Carbon dioxide
EC	Electrical conductivity
FAO	Food and Agriculture Organization of the United Nations
GHG	Greenhouse gas
GOTS	Global Organic Textile Standard
ICAC	International Cotton Advisory Committee
IISD	International Institute for Sustainable Development
IPCC	Intergovernmental Panel on Climate Change
IPM	Integrated Pest Management
ISCC	International Sustainability and Carbon Certification
IUCN	International Union for Conservation of Nature

N	Nitrogen
N_2O	Nitrous oxide
NGO	Non-governmental organization
NRCS	Natural Resources Conservation Service
MAP	Mean annual precipitation
MAT	Mean annual temperature
MBC	Microbial biomass carbon
MBN	Microbial biomass nitrogen
OCS	Organic Content Standard
OECD	Organisation for Economic Co-operation and Development
P	Phosphorus
PET	Potential evapotranspiration
Ph	Physical
POXC	Permanganate oxidizable carbon
RA	Regenerative Agriculture
ROC	Regenerative Organic Certified
RT	Reduced tillage
S	Sulfur
SH	Soil health
SOC	Soil organic carbon
SOM	Soil organic matter
THS	Turbo Happy Seeder
TN	Total nitrogen
US	United States of America
USDA	United States Department of Agriculture

CHAPTER 1

INTRODUCTION

"Cotton represents so much more than just a commodity: it is a culture, a way of life, and a tradition that finds it roots at the heart of human civilization"

- FAO Director-General Qu Dongyu, 2019

Soils, fashion, and agriculture are more connected than is often realized. Cotton is the most widely grown non-food crop, the leading natural fiber in the manufacture of textiles since the 19th century, and an important cash crop in many countries. Grown mainly for its fiber, the cotton crop also produces oil and seeds that can be used for animal feed. In 2020, 83 million tons of seed cotton were produced globally on 31.8 million hectares of land (FAOSTAT, 2022a), in a diversity of soil types and climatic conditions. Cotton is a source of income for 100 million family farmers (IISD, 2020) in over 80 countries (Cotton Analytics, 2022). The cotton sector has an annual turnover of around $50 billion and constitutes approximately 31% of the global textile market (Acclimatise, 2021) making it the second most used fiber since fossil fuel-derived polyester fiber consumption surpassed cotton in the mid-1990s.

Agriculture has become one of the most intensive forms of land use (Orgiazzi, 2017). Conventional cotton production systems are characterized by monoculture, intensive tillage, heavy mechanization in some countries, dependence on fossil fuels, and excessive use of agrochemicals to manage pests, weeds, and nutrient levels. As a result, long-term cultivation has resulted in depletion of soil organic matter (SOM) and nutrients, soil erosion, decline in soil biological diversity, increased pest attack, groundwater pollution, falling water tables, increased salinization, rising greenhouse gas (GHG) emissions and declining yields in many regions.

Environmental degradation is a serious threat to cotton systems. With cotton production projected to increase (OECD-FAO, 2021), it is critical to ensure that cotton production does not contribute to deterioration of soil health and further GHG emissions are prevented. The fashion industry is waking up to the fact that emissions reduction targets and commitments to reversing biodiversity loss cannot be met without addressing soil health at the very beginning of fashion value chains. Adoption of better agronomic practices will be critical to ensuring that both yield increases, and environmental protection are achieved. With a growing and increasingly affluent global population, limited arable land, declining soil health, and climate change, this is both a challenging and timely discussion.

1.1 Sustainable agriculture terminology

This paper adopts the IUCN (2020) notion that sustainable agriculture should agree with the definition of sustainable development, and therefore "*sustainable agriculture should be able to meet the current needs of society without compromising the ability of future generations to meet their own needs*." Consistent with this definition, the FAO (2014) have proposed the following five principles for sustainable agriculture:

1) Improving efficiency in the use of resources.
2) Conserving, protecting, and enhancing natural ecosystems.
3) Protecting and improving rural livelihoods and social well-being.
4) Enhancing the resilience of people, communities, and ecosystems.
5) Promoting good governance of both natural and human systems.

There are several popular terms that describe different pathways towards the future of farming, many of which are shown in Figure 1.

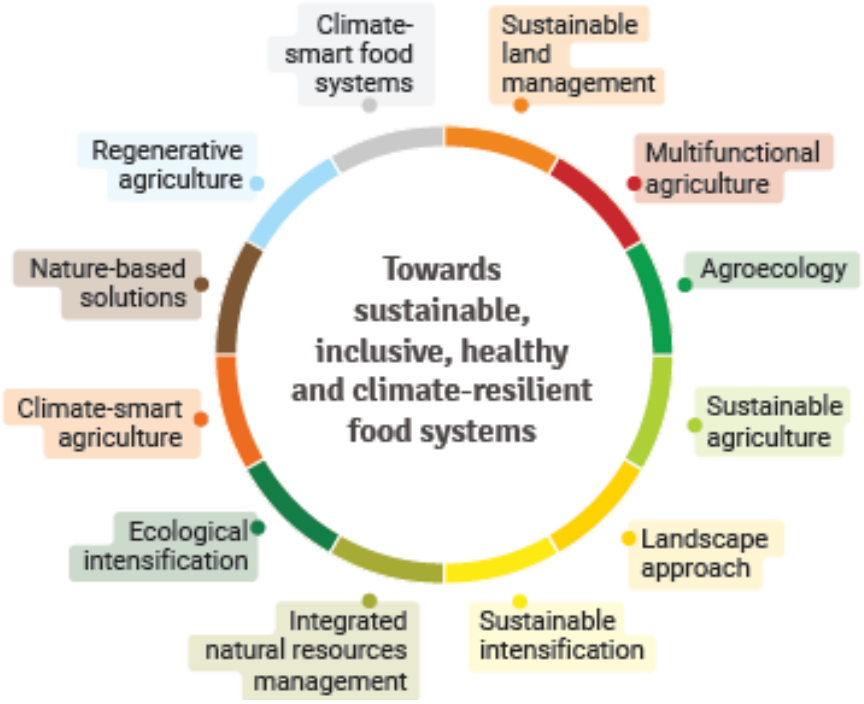

Figure 1. Terms used to describe approaches to sustainable agriculture. *Source: Steiner et al. (2020)*

The abundance of terminology associated with sustainable agriculture is often the subject of debate, diverting attention away from the effective transition to truly sustainable forms of agriculture (IUCN, 2020). These narratives often share similar high-level goals, such as improving food security, reversing environmental damage, and reducing use of external inputs, but have different emphases. Some emphasize different practices while others emphasize particular environmental or societal outcomes.

Sustainable Intensification is an outcome objective that aims to increase productivity on existing agricultural land through more efficient use of natural resources and technologies that also improve environmental conditions. Climate-Smart Agriculture (CSA) also has an emphasis on productivity, but set under the new realities of climate change. CSA is defined as "*an agriculture that sustainably increases productivity, enhances resilience (adaptation), reduces/removes greenhouse gases (mitigation), and enhances achievement of national food*

security and development goals (Zougmore et al., 2021). According to CCAFS (2022), "*CSA is not a set of practices that can be universally applied, but rather an approach that involves different elements embedded in local contexts*." Agroecology, on the other hand, has more of a focus on equity, access, and human welfare than other sustainable agriculture frameworks.

One approach that is gaining momentum is Regenerative Agriculture (RA). Despite RA not having a comprehensively described scientific or regulatory definition (Elevitch et al., 2018), it is receiving attention from retailers, researchers, consumers as well as politicians and the mainstream media (Newton et al., 2020), often promoted as an agricultural paradigm that can reduce reliance on fossil fuels, increase soil carbon sequestration, increase productivity, and achieve net positive environmental and/or social outcomes. Within the fashion industry, there are a number of RA programs focusing on materials such as cotton, wool, rubber, and leather as well as RA-specific initiatives and funds that aim to accelerate the transition to RA within apparel, textile, and footwear value chains. However, there is a lot of variation with the RA framework where different users give the term different meaning. In a review of definitions of RA in peer-reviewed literature, Schreefel et al. (2020) found that the dominant objectives mentioned were about improving environmental issues. The theme of enhancing and improving soil health received the most attention, and there was a strong convergence of themes around optimizing resource management, alleviating climate change, and improving water quality and availability. In another review, Newton et al. (2020) found a differentiation between descriptions of RA based on practices, such as use of cover crops or integration of livestock, while others focused on outcomes, such as to improve soil health, to sequester carbon and to enhance biodiversity.

A closely related approach to RA is Conservation Agriculture (CA), which is described by the FAO (2021a) as "*a farming system that can prevent losses of arable land while regenerating*

degraded lands". In contrast to RA, CA does have a widely recognized definition. It is defined by three principles: minimal soil disturbance, permanent soil cover, and crop diversification. CA is one of the climate mitigation solutions identified by Project Drawdown, a science-based climate change mitigation project, that will help the world reach "drawdown" – the point at which GHG concentrations in the atmosphere stop climbing and start to steadily decline. It projects the total area under CA will increase from 148 million hectares to peak at 400-327 million hectares by 2035, reducing carbon dioxide (CO_2) equivalent emissions by 12.81-8.08 gigatons based on average carbon sequestration rates of 0.25-0.78 metric tons of carbon per hectare per year, depending on the region (Project Drawdown, 2022). Within the Project Drawdown framework, CA is seen as a bridge to regenerative annual cropping, which builds on CA and involves additional practices such as compost application, organic farming, or green manure use.

Although CA adoption has been increasing globally and is now practiced in approximately 78 countries (Kassam et al., 2018), in some regions it is slow or non-existent (Farooq and Siddique, 2015). Reasons for this include lack of CA extension services, technical knowledge, institutional support, access to equipment, or cultural aspects in changing mindsets. Moreover, many have questioned the feasibility of CA adoption in smallholder contexts as well as the role that specific site and soil conditions play in the success of CA. Furthermore, appropriate management, such as frequent weeding and early planting, and understanding decision-making at the household level are important success factors (Gatere et al., 2013), calling for CA to be adopted with pragmatism (Kirkegaard et al., 2014). These arguments will be returned to in the discussion section.

Conservation Agriculture is the focus of this paper due to its clear definition and volume of global research in cotton-based systems compared with Regenerative Agriculture and other mentioned approaches. Furthermore, many of the mentioned sustainable agriculture frameworks promote minimal tillage, crop diversity, and cover crops as practices that can help to achieve the desired high-level goals, amongst others. With this context, CA is used a general term to describe a set of well-studied soil conservation practices that have relevance for multiple alternative agriculture frameworks. There are many opportunities for other practices and approaches depending on the context, which will be mentioned throughout the paper.

1.2 Objectives

The goal of this capstone is to drive evidence-based and site-specific approaches to land management and policy to improve soil health and productivity of cotton production systems, to improve farmer livelihoods, and to sustain cotton value chains for the future.

This paper evaluates the academic literature regarding CA in cotton production systems. All selected publications were integrated into a new database, sorted by cropping system, country, soil type, and climate region. Recommendations are summarized and discussed as well as critically assessing where these studies have taken place, which indicators were measured, and where gaps in research remain.

The dataset can be used by farmers, researchers, extension agents, policy makers, private sector, and sustainability practitioners for further stakeholder engagement as they plan and evaluate sustainable land use management in cotton-based systems.

The objectives of my paper are three-fold:

1) To compile, synthesize and review existing CA research in cotton cropping systems.

2) To discuss the learnings and implications of the research for the fashion industry's ambition to promote regenerative farming systems.
3) To identify gaps in research, particularly in important cotton production regions most under threat from climate change or that will help to build towards a vision of sustainable agriculture.

1.3 Key principles of soil health

Soil health refers to the ability of soils to function as a biodiverse organism that sustains terrestrial life (USDA, 2022). It encompasses physical, chemical, and biological properties of soil (Figure 2), that are dynamic and constantly interact to enable soils to function as a vital living ecosystem that provides important ecosystem services.

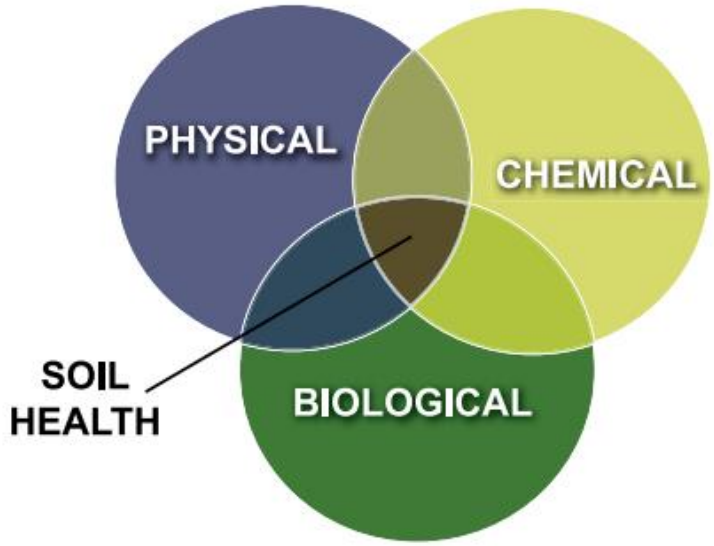

Figure 2. Concept of soil health as the integration of physical, chemical, and biological components of soil. *Source: Moebius-Clune et al. (2016)*

Soil health indicators are measurements that represent the soil conditions and ability of soils to perform ecosystem functions. These basic functions include (USDA, 2022):

(1) Promoting biodiversity activity and productivity.

2) Filtering, buffering, degrading, and detoxifying organic and inorganic materials.

(3) Controlling the regulation and partition of water and solute flow.

(4) Cycling carbon and nutrients.

(5) Providing physical stability for plants and animals as well as providing support for structures associated with human habitats.

Soil indicators are divided into physical, chemical, and biological categories (Table 1).

Table 1. Physical, chemical, and biological soil health indicators

Category	Examples of indicators
Physical	Aggregate stability, bulk density, porosity, penetration resistance, infiltration, available water holding capacity
Chemical	pH, soil organic carbon (SOC), total nitrogen (TN), cation exchange capacity (CEC), extractable macronutrients, electrical conductivity, soil nitrate
Biological	Microbial biomass carbon (MBC), microbial biomass nitrogen (MBN), soil respiration, enzyme activities, active carbon, particulate organic matter, potentially mineralizable nitrogen

Soil physical properties relate to the structure of soils, which is largely influenced by the distribution and stability of soil aggregates. Living organisms play a key role in binding soil particles together and stabilizing them into aggregates. For example, arbuscular mycorrhizal (AM) fungi physically enmesh soil particles together to form macroaggregates through their extensive branching hyphal networks. Ecosystem engineers, such as earthworms, contribute to aggregate formation through their castings and physical mixing of organic matter and residues. Soil aggregates influence **bulk density**, **porosity**, and the size of pores – the spaces in soil that are filled with either water or air. Aggregates can also physically protect SOM from decomposition, increasing the residence time of soil C (Rillig et al., 2001). A well-structured soil is one that has high **aggregate stability** to resist disintegration when hit by rain drops, and a mixture of macropores and micropores to create a balanced environment of water **infiltration** and **water holding capacity**, airflow, retention of nutrients and good root growth.

Chemical components of soils affect the reactions and processes that occur within soils such as cycling of carbon and nutrients, filtering, and regulating water cycles. **pH** measures the acidity or alkalinity of soils and affects many soil characteristics such as the availability of nutrients, solubility and toxicity of heavy metals, and habitability of soil environments for certain microbial communities. Soil pH also influences the **cation exchange capacity**, the capacity of soils to hold onto essential nutrients, as well as the buffering capacity of soils to resist further changes in pH. **Electrical conductivity** is another commonly used chemical indicator that measures soil salinity through the ability of soil water to carry an electrical current.

A diverse and active biological environment is important for enhancing soil health. Orgiazzi et al. (2016) summarize the importance of soil microbes and fauna to soil functions and how they interact with physical and chemical soil components:

"*…microbes are the ultimate operators of all chemical transformations in the soil: they facilitate nutrient release through decomposition processes, conservation of organic matter through synthesis of resistant humic compounds, and nitrogen fixation…Invertebrates play a unique role in mechanical activities by softening, fragmenting and burying plant residues, which facilitates their natural decomposition, and creating channels and pores in the soil that provide habitats for smaller organisms and reservoirs and routes for air and water to circulate and be stored. In addition, invertebrates produce compounds that stimulate plant growth and protection against pests and diseases*"

Given their importance in governing soil functions, when soil microorganisms are affected by management practices or changes in their environment, so too is soil health. Biological indicators provide insight into the living components of the soil and tell us about soil processes that are mediated by soil organisms. These indicators can reflect the number, type, and

activity of soil microorganisms as well as the diversity of microbial life (USDA, 2022). **Microbial biomass carbon** and **microbial biomass nitrogen** measure microbial abundance through quantification of carbon and nitrogen contained within microorganisms. **Soil respiration**, on the other hand, is more of a measure of activity than abundance. It is measured by re-wetting air dried soil and quantifying the CO_2 produced, as an indicator of how active the soil microbial community is. **Active carbon**, also known as permanganate oxidizable carbon (POXC), measures the portion of organic matter that is readily available as a food source for soil microbes.

Figure 3 depicts the role of different soil biota in important soil processes and functions that maintain ecosystems and the provision of benefits that humans obtain from them.

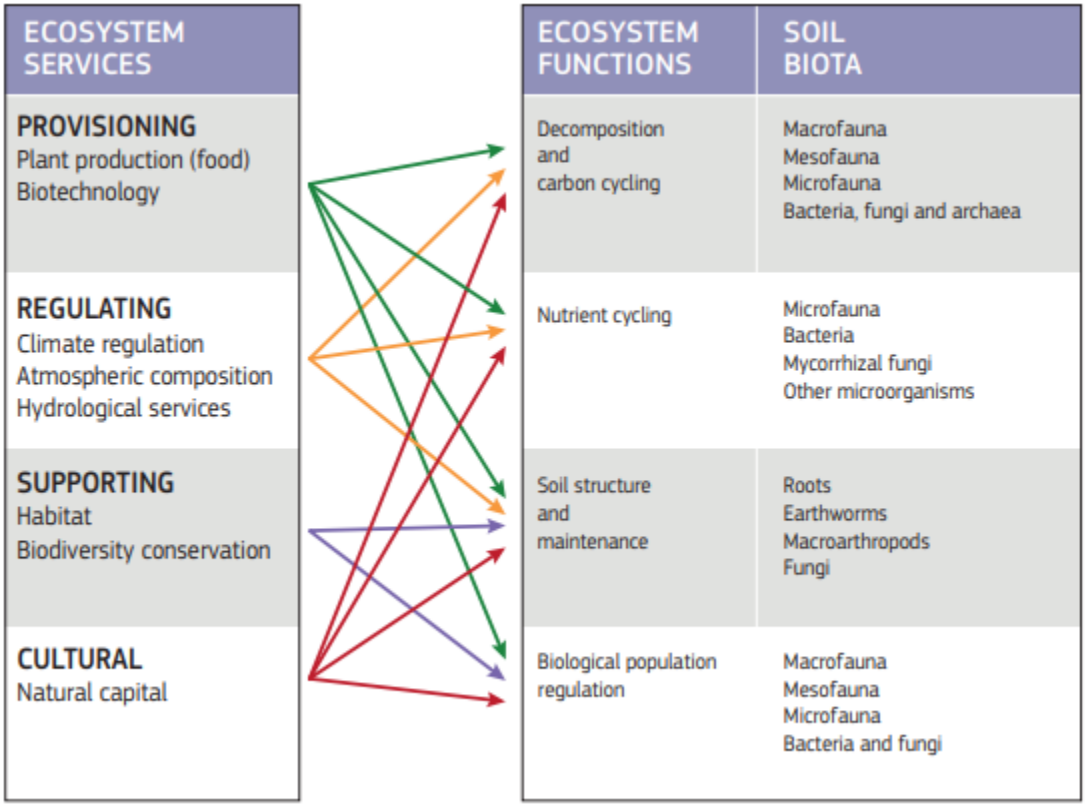

Figure 3. Soil-based ecosystem services, ecosystem functions, and the soil organisms that support them. *Source: Orgiazzi et al. (2016)*

Within the soil science and agricultural communities, the importance of soil physical and chemical properties has been well accepted. Standard soil test analysis packages typically measure pH levels and nutrient analyses. These measure nutrient levels in soils and recommend application rates for the nutrients that may be limiting plant growth. However, these tests do not reveal much information about overall soil health or identify constraints beyond chemical components of soil. It has not been until more recently that the importance of understanding the soil's biological properties has been more broadly accepted (Moebius-Clune et al., 2016). More comprehensive assessments of physical, chemical, and biological properties and processes give a more holistic understanding of soil health and better identifies constraints.

1.3.1 Soil carbon

It is commonly assumed that SOM, the portion of soil that is composed of living and dead plants and animals in various states of decomposition, contains 58% carbon though this can vary by soil type and component of SOM (Pribyl, 2010). Conventional agriculture has typically depleted soil C stocks by removing organic matter through harvesting and returning less plant litter, increasing decomposition of SOM through intensive tillage and intensifying soil loss through erosion. Growing awareness of the contribution of agriculture to global GHGs and the potential of soils to store carbon and therefore play a role in climate regulation, has fueled an intensified interest in managing soils to increase SOC sequestration and rebuild soil C pools.

It is the decomposition of SOM that releases carbon and other nutrients for plants and microorganisms to access. While primary production and photosynthesis are important for fixation of C and transport into soils, soil microbes play a critical role in regulating C flows and SOC accumulation, as well as many other important ecosystem processes, via mineralizing residues and immobilizing nutrients through their symbioses with plants. Increasing SOC

therefore both removes CO_2 from the atmosphere and builds organic matter. However, there is a trade-off between carbon storage and microbial activity where increasing microbial activity reduces the C stock as C is used for metabolic activity, and some CO_2 is respired back out to the atmosphere. This dilemma is described by Janzen (2006):

"*…we say we want to store more organic C; we say that will make the atmosphere cooler and the soil better. But organic matter is the most beneficial, biologically, as it dissipates by microbial activity. With constant C inputs, we cannot both increase soil C and increase microbial activity. If we want higher microbial activity, we have to sacrifice soil organic C; if we want to store more C, we must quash microbial activity*."

Net increases in SOC therefore requires increasing C inputs or decreasing losses from slowing decomposition, or both (Paustian et al., 1997). Interest in sustainable agriculture approaches has been accompanied by interest in measuring impacts of interventions on SOC. In a review of 20 SOC studies in cotton production systems of the Southeastern United States, Causarano et al. (2006) found that conservation management practices such as no-till, rotations of cotton with high-residue producing crops, and using a cover crop were most effective in increasing SOC. Using a cover crop in combination with conservation tillage doubled the C sequestration benefit compared to using conservation tillage alone.

SOC is an important soil health indicator – it is relatively easy to quantify, and it is related to, and therefore indicative of, many other indicators. Growing acknowledgement of the importance of soils as a C sink and role in stabilizing GHG emissions within safe boundaries has driven a lot of research to focus on the influence of management practices on SOC. However, focusing on SOC as the only objective and indicator is dangerous. There are a wide range of estimates of the potential of C storage in soils, however many scientists agree that soil C sinks

can only, at best, have modest effects on atmospheric CO_2 by the end of this century. It is also important not to overlook other agricultural emissions, such as from animal manure, machinery use, or relating to the manufacture and application of fertilizer, liming, irrigation, and pesticides, let alone other environmental and social outcomes. Nevertheless, management to build up SOC is beneficial for slowing the rise of atmospheric CO_2 as well as increasing productivity and the capacity for soils to provide other critical ecosystem services.

1.4 A brief history of Conservation Agriculture

The term 'Conservation Agriculture' was coined in the 1990s, but the importance of soil protection through minimized disturbance and keeping soils covered was borne out of the 1930s Dust Bowl in the US (CIMMYT, 2022). In 1935, the USDA estimated that 50 million acres of farmland had been abandoned due to soil erosion, where poor management practices and heavy use of labor-saving machinery had increased erosion by up to 800 times the soil replacement rate (Montgomery, 2007). In the aftermath, soil conservation began to be considered as an issue of national survival. The development of seeding machinery that made sowing possible without tillage emerged in the 1940s (Friedrich et al., 2012). Over time, CA was increasingly adopted in the US to combat drought-induced or management-induced soil erosion or due to rising fuel prices (Farooq and Siddique, 2015). In the 1970s, no-till farming reached Brazil and began to be tested in West Africa, South Africa, and South America. Adoption accelerated in the 1990s in Argentina, southern Brazil, and Paraguay, gaining the attention of international organizations due to its positive results for crop yields, farmer income, and environmental sustainability. Several international organizations and NGOs went on to play an important role in the promotion of CA farming in Zambia, Kenya, Tanzania, India, China, Pakistan, and Kazakhstan. As of 2015/16, approximately 180 million hectares of agricultural land was cropped according to CA principles,

corresponding to about 12.5% of total global cropland, an increase of more than 69% since 2008/09 (Kassam et al., 2018).

1.5 Key principles of Conservation Agriculture

CA is an agroecological approach that is based on three core principles:

1) Minimize soil disturbance

Conventional tillage inverts and breaks up soil. It is often used to prepare seedbeds, control weeds, improve crop establishment and/or incorporating fertilizers. It also increases rates of decomposition of SOM, increasing the availability of nutrients to microbes and plants. However, heavy soil disturbance is detrimental to soil health by destroying soil structure, disrupting macroaggregates, increasing the vulnerability of soils to erosion, and reducing the ability of soils to store water and nutrients. Machine traffic causes soil compaction, reducing pore space in soils that are important for water infiltration, aeration, root growth and supporting microorganisms. Intensive tillage also disturbs the development of fungal hyphae that are important for aggregate stability, nutrient cycling and often have symbiotic relationships with plants.

CA promotes minimal soil disturbance through reduced or zero tillage, which involves direct planting without plowing or preparing the soil. This can improve soil structure, aggregate stability, water infiltration, aeration, reduces erosion and increases soil biological activities. The reduction in machinery usage also reduces fuel use, resulting in lower GHG emissions as well as time and production costs.

2) Permanent soil cover

Crop residues are the principal element of soil cover. When crop residues are retained and left on the soil surface, they protect topsoil from erosion, reduce runoff, reduce weed pressure, improve nutrient availability, and help to maintain an active microbial community that can

improve SOM and perform essential soil functions. When residues decompose, they release carbon (C), nitrogen (N), phosphorus (P), sulfur (S) as well as other macronutrients and micronutrients that plants require for healthy growth (Al-Kaisi and Lal, 2017). As cotton is a low residue crop, maintaining a soil cover and crop residue management is a critical part of sustainable agricultural systems for cotton. This can be done by growing cover crops or inter-crops, especially high residue returning crops, within wide row spaced cotton or recycling of crop residue of the previous crop, such as wheat. Over time, these residues can increase organic matter content, and therefore SOC, by adding fresh organic material and reducing soil erosion. In rainfed regions, the purpose of retaining a cover or residue mulch is often to maintain soil moisture and reduce water loss from evaporation.

3) Crop diversification

Monoculture cropping has become a common practice in industrial agriculture as it has enabled increased efficiencies in planting and harvesting and increased yields. However, it has significantly reduced the diversity of crops and led to a reliance on agrochemical inputs to prevent the buildup of pests and diseases. Increased diversity aboveground and belowground is important for promoting a diverse microbial community and is increasingly seen as an important strategy for addressing issues of long-term agricultural sustainability and building resilience. Rotating cotton with other crops can improve soil structure through different root architectures and exudates, enhances nutrient cycling, break pest and disease cycles, and other crop-specific benefits such as biological fixation of N helping to reduce reliance on synthetic fertilizers. Common methods are intercropping or companion planting, where two or more crops are grown at the same time on the same land, or crop rotation, where different crops are grown on the same land but in a sequential manner.

1.6 Background on cotton production

1.6.1 Cotton physiology and growing conditions

Cotton is a woody perennial that originated in arid regions of the tropics and subtropics. It is now grown as an annual crop where "*due to man's influence, the cultivated linted species have changed from the stationary, almost relic state of the lintless species to an aggressive colonizing phase with vast planted populations which has spread them into more mesophytic habitats and varied climatic conditions*" (Purseglove, 1968). Since its annual habit was developed, cotton production has spread to more temperate regions and adapted to many different agro-climatic conditions.

Cotton belongs to the family Malvaceae and the genus *Gossypium*. The exact origin of the species of *Gossypium* is the subject of much controversy without consensus. This genus has approximately 54 species, but only four are domesticated and grown commercially. The four cultivated species are:

- *Gossypium barbedense* L. (Egyptian cotton)
- *Gossypium herbaceum* L. (Asiatic cotton)
- *Gossypium arboreum* L. (Arabian cotton)
- *Gossypium hirsutum* (Upland cotton)

Each species varies in length of fiber and other fiber quality characteristics that determine product suitability, as presented in Table 2. High yield of lint and good fiber quality have typically been the primary goals of breeders and growers. Yield is determined by the number of bolls per plant, size and weight of bolls, earliness, ginning out turn as well as diseases, pests, and other harvesting losses. Fiber quality characteristics include fiber length, strength, uniformity,

and micronaire, which refers to the thickness of the cell walls of cotton fibers and is used as an indicator of fiber fineness and maturity.

Table 2. Comparison of the four cultivated cotton species

Cotton	Fiber Length	Yarn Count (Ne)	Yarn Type	Cultivation Country (Organic)	Product Suitability
Gossypium Arboreum	Short	3–20	OE, K	Benin, Bukian Faso, India, Mali, Pakistan, Peru, Senegal, Tanzania, Uganda, USA	Denim/Jeans, Home, Canvas, Non-Wovens, Medical, Industrial textiles
Gossypium Herbaceum	Short	3–20	OE, K	Benin, Bukian Faso, India, Mali, Pakistan, Peru, Senegal, Tanzania, Uganda	Denim/Jeans, Home, Canvas, Non-Wovens, Medical, Industrial textiles
Gossypium Hirsutum (Upland)	Medium, Long	18-45	K, C, CK	Benin, Brazil, Bukina Faso, China, Colombia, India, Madagascar, Mali, Pakistatn, Peru, Senegal, Tajikistan, Tanzania, Turkey, Uganda, USA	Denim/Jeans, Home, T shirts, Yoga wear, Leisure wear, Causal wear, Under wear, Industrial, Smart, Geo textiles
Gossypium Barbadense	Long, Extra Long	40-130	K, C, CK	China, Egypt, India, Israel, Kyrgyzstan, Madagascar, Peru, Turkey, USA	High-end (fine apparel, underwear/intimates), High-end Home

OE - Open end/Rotor yarn | K - RIng spun carded yarn | C - RIng spun combed yarn | CK - RIng spun combed compact yarn

Source: Kering & Textile Exchange (2017)

Upland cotton is the most cultivated species around the world, accounting for 95% or more of total global production (Snider et al. 2021), due to its high yields, responsiveness to fertilizers, and its application for a wide range of products. *G. herbaceum* is a short staple cotton native to sub-Saharan Africa and Arabian Peninsula. On the other end of the spectrum, *G. barbadense* produces an extra-long staple fiber and is mostly grown in Egypt and Turkey. The most luxurious cotton products are made with extra-long staple fibers. *G. arboreum* is a shorter staple fiber compared to upland cotton and has its origins in India where it was traditionally the dominant cotton species until Indian Independence in 1947. After Independence, upland cotton, hybrid seeds and chemical fertilizers began to dominate cotton farming in India. To this day, India is the only country in the world that cultivates all four cotton species as well as hybrid cotton. While *G. hirsutum* dominates, *G. herbaceum* is still cultivated in parts of Gujarat, and *G. barbadense* is confined to a limited area in South India (Blaise and Kranthi, 2020).

The crop growth stages of cotton are shown in Figure 4. The length of the growing period is about 150-190 days. 50-85 days are required for first bud formation after planting, 25-30 days for flower formation, and 50-60 days from flower opening to mature boll (Snider, 2021). It has an indeterminant growth habit in which both vegetative and reproductive growth occur simultaneously, making it difficult to make a clear distinction between crop growth stages.

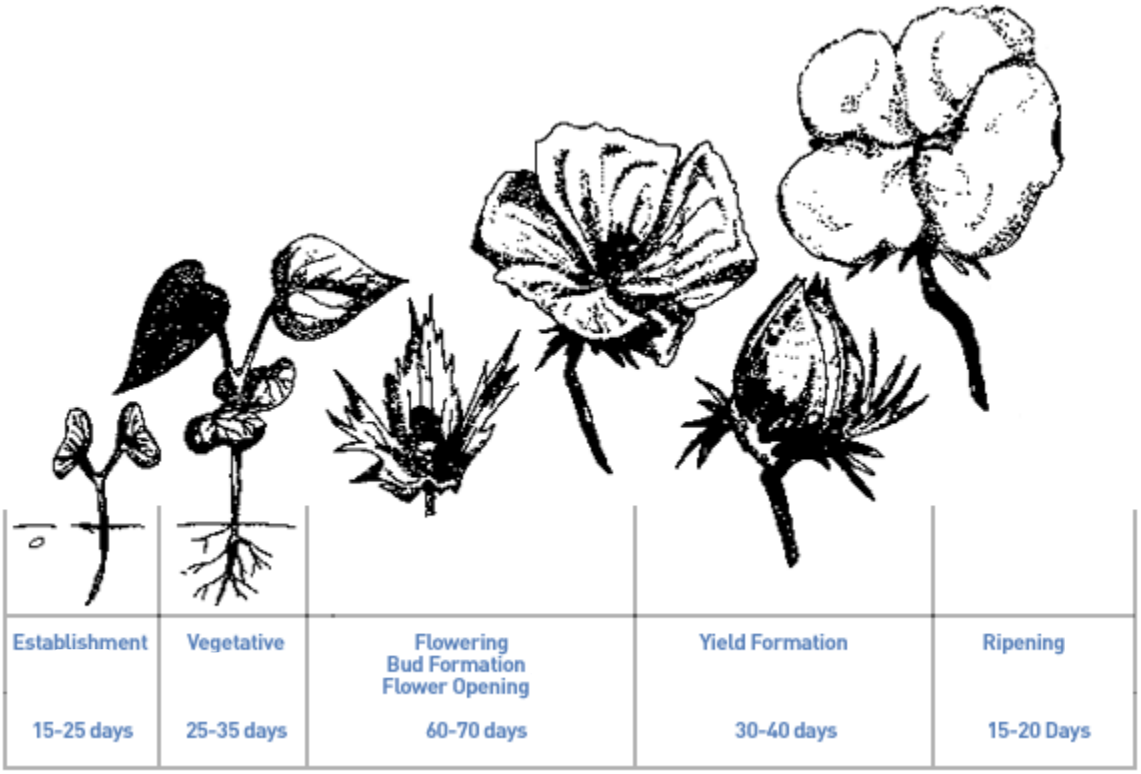

Figure 4. Cotton growth stages. *Source: FAO (2021b)*

Cotton ideally grows between minimum temperature of 12-15°C and maximum temperature of 40°C and requires a minimum of 200 frost-free days (FAO, 2021b). The main abiotic constraints on good cotton growth are temperature and water availability. However, light intensity is also an important growth factor, where shading from interplanted crops or too dense a stand affects flowering, fruiting and increases boll shedding. Despite being fairly heat tolerant, temperatures over 28-30°C can affect yields especially during the flower formation stage, reducing fruit retention, seed number and boll size (Brown, 2008).

While cotton is often referred to as a water-intensive crop, its water needs can vary drastically and, while higher than most staple crops, are not as high as some other agricultural crops such as alfalfa, banana and sugarcane (see Table 3). Having adequate but not excessive moisture is particularly important for early vegetative growth and boll swelling, while the first flowering period, ripening and harvest requires relative dryness. An assessment of the impact of projected climate change on global cotton production found that 75% of cotton regions will experience increased heat stress and 50% will experience increased drought risk by 2040 while extremes in rainfall will present increased risk for some of the most productive cotton growing regions (Acclimatise, 2021).While cotton is among the more drought tolerant row crops, it cannot tolerate very heavy rainfall, especially during flowering, which is a particularly pertinent challenge given changing precipitation patterns under climate change.

Table 3. Indicative values of crop water needs and sensitivity to drought.

Crop	Crop water need (mm/total growing period)	Sensitivity to drought
Alfalfa	800-1600	low-medium
Banana	1200-2200	high
Barley/Oats/Wheat	450-650	low-medium
Bean	300-500	medium-high
Cabbage	350-500	medium-high
Citrus	900-1200	low-medium
Cotton	700-1300	low
Maize	500-800	medium-high
Melon	400-600	medium-high
Onion	350-550	medium-high
Peanut	500-700	low-medium
Pea	350-500	medium-high
Pepper	600-900	medium-high
Potato	500-700	high
Rice (paddy)	450-700	high
Sorghum/Millet	450-650	low
Soybean	450-700	low-medium
Sugarbeet	550-750	low-medium
Sugarcane	1500-2500	high
Sunflower	600-1000	low-medium
Tomato	400-800	medium-high

Source: FAO (2022b)

In terms of biotic constraints, cotton is extremely sensitive to pests. Major pests causing significant economic damage are bollworm, leafhoppers, and whitefly. Bollworms are the most serious pests of cotton, where they feed in the bolls causing damage to the lint and seed and therefore reducing yield and fiber quality. While genetic improvement has focused on pest resistance with relative success with Bt cotton, bollworm resistance to Bt-toxins is being reported (Kranthi, 2015) as well as widespread use of Bt cotton leading to higher susceptibility of cotton crops to other, previously minor, pests such as aphids, thrips, leafhoppers, and whiteflies, which are increasingly resistant to insecticides (Kranthi et al., 2002). Major diseases include bacterial blight, fusarium wilt, verticillium wilt and leaf curl which is transmitted by the whitefly.

1.6.2 Global distribution of cotton production

Cotton is an extensively produced fiber and is now grown all over the world. The top five producers in production season 2021/22 were India, China, US, Brazil, and Pakistan (see Figure 5). India is the largest cotton producer both by quantity and production area. When combined, these five countries account for more than three-quarters of global cotton production.

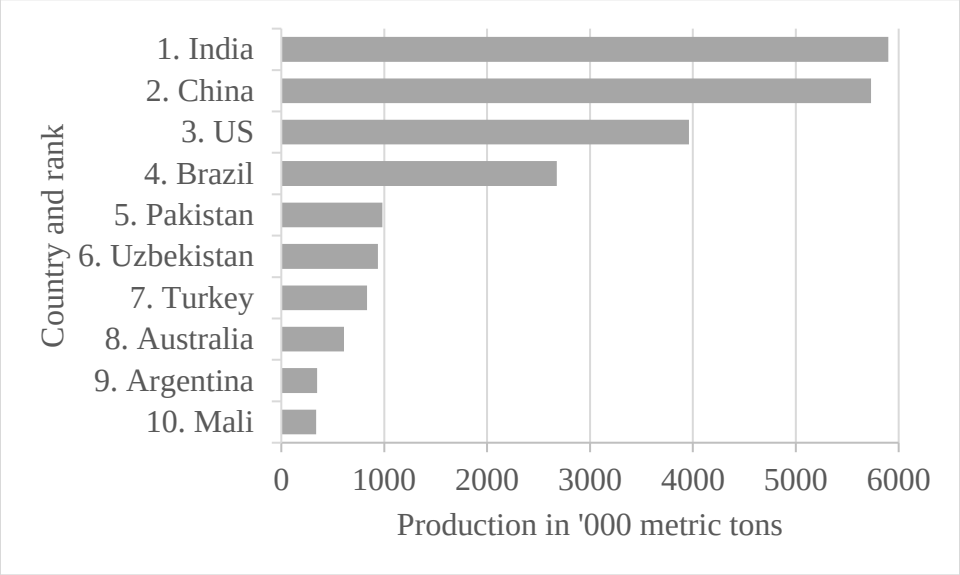

Figure 5. Global cotton lint production in 2021/22. *Source: ICAC (2021)*

Cotton yields have been increasing since the beginning of the 20th century largely due to genetic improvement, increase in inorganic fertilizer usage, as well as insecticides and herbicides. However, as shown in Figure 6, global yields have been relatively flat since 2004 largely due to pest pressures and water scarcity (OECD-FAO, 2021). Despite being the dominant cotton producer, India's average yields have been consistently below the global average. On the contrary, both Brazil and China have the highest yields and lower total harvested area compared to both India and the US. While China's total harvested area has been declining, Brazil's rise in both area harvested, and yields signals its rising importance as a global producer. In terms of exports, Brazil has risen in recent years from fifth largest to second largest cotton exporter,

second only to the US. Top importers of cotton are China, Bangladesh, and Vietnam (ICAC, 2021).

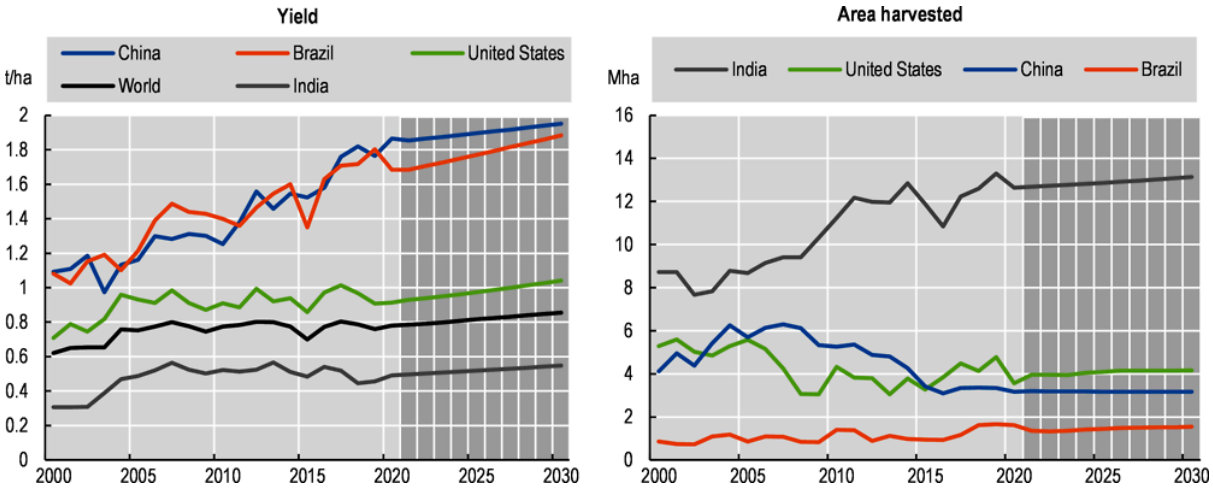

Figure 6. Historic and projected cotton yields and area harvested in major producing countries. *Source: OECD-FAO (2021)*

1.6.3 Effects of long-term continuous cotton cropping on soil health

Intensive agricultural operations, natural vegetation removal, and water and wind erosion are main factors behind cropland soil degradation. According to the FAO, one-third of global soils are infertile due to unsustainable land-use management (FAO, 2011). In every country where cotton is grown, cotton production is constrained by pests and diseases, weed pressures, increasing resistance in insects and weeds, severe soil degradation, and increased frequency and severity of droughts, floods, and heat waves. Like many other crops, industrial cotton farming has been a driver of land conversion, soil erosion, pollution, GHG emissions, and loss of biodiversity. Intensive continuous cotton systems using conventional tillage, with up to 4-5 machinery passes, have experienced degradation of soil physical, chemical, and biological properties. In addition, poorly managed flood irrigation and excessive use of chemical inputs are typical of conventional land use practices.

Putting management-related impacts aside, cotton as a crop is perceived as an environmentally demanding crop that does not naturally have many benefits for soil. It has a deep tap-root system that can extend to a depth of 1-2 meters, depending on soil structure and height of water-table. This deep root system enables cotton plants to access groundwater reserves during drought periods and can improve light soil compaction issues in some instances. However, its root architecture does not bind soils together or easily access nutrients due to low density of lateral roots and roots in the surface soil layers where nutrient availability is highest.

One of the core soil conservation principles is the retention of crop residues on the surface as soil cover. Field crops such as wheat, soybean and maize produce a substantial amount of crop residue, making their retention on the soil surface relatively straightforward. On the contrary, cotton produces few residues. After picking, about 1.4-2 Mg/ha of cotton crop residue is left in the form of stalks and leaves (Blaise, 2015). To compare, residue incorporation in rice-wheat systems can involve 6-12 Mg/ha of crop residue (Prasad et al., 1999). In addition, the high lignin content, less soluble C, and high C:N ratio of cotton stalks means they are slow to decompose. Furthermore, there are often competing uses for cotton crop residues, such as animal feed or biofuel, or are disposed through burning to manage pest and diseases.

Pest pressures, particularly bollworm infestations, are a significant challenge to cotton growers worldwide. It is estimated that cotton accounts for 16% of all global insecticide usage (Environmental Justice Foundation, 2017). When used in excessive amounts, these chemicals can cause water pollution as well as harming the health of farm workers and disrupting natural biological cycles. In a study of microbial community structures under different 12-year cropping sequences, continuous cotton systems were found to have less diverse assemblages compared to continuous soybean, continuous corn, and a corn-soybean rotation, potentially due to the

increased use of pesticides during cotton sequences (Ashworth et al., 2017). Tillage is commonly used to control pests. However, as a management practice, it alters soil properties such as soil structure, which in turn changes the ability of soil to store water and increases the susceptibility of soil to erosion and evaporative losses.

Compared to other annual crops, cotton is considered a greater soil erosion hazard. Data from the Guthrie research station in Oklahoma showed that the fine sandy loam eroded more than ten thousand times faster under cotton cultivation than native grass (Montgomery, 2007). Soil erosion strips away the most nutrient and organic matter-rich topsoil and causes reductions in soil productivity, soil fertility and can pollute nearby water sources. Cotton yields can decline by up to 4% for each centimeter of topsoil loss (Brown et al., 1985), threatening the sustainability of the overall crop production system. As a result, practices that rebuild SOM are central to almost all the sustainable agriculture approaches mentioned in Section 1.1.

1.3.4 Cotton outlook

Rising populations, economic growth and urbanization in developing and emerging economies is projected to increase per capita demand for cotton textiles. World cotton production is projected to grow 1.5% per annum, reaching 28 million tons of fiber production in 2030 (OECD-FAO, 2021). Two-thirds of this growth is projected to result from increased yields as opposed to expansion or conversion of land used to grow cotton, though this varies by country (OECD-FAO, 2021):

- **India**: production is expected to increase through rising yields rather than expansion of area. Currently constrained by insect pests, diseases and adverse weather, growth in yield is projected to be realized through increased use of smart mechanization, varietal development, and pest management practices. Climate change, and particularly changing

rainfall patterns, is a major threat to this yield growth where 65% of cotton is rainfed (Blaise and Kranthi, 2020).

- **Brazil**: growth in production will come from expansion of cotton area with some capacity to further increase already high yields (OECD-FAO, 2021). However, cotton has been expanding from the fertile soils in the southern regions to less fertile soils in the humid savannas of the Mato Grasso region (Séguy, 2014), which could affect yield improvement potential. Land conversion is the largest source of agricultural GHG emissions, with depleted soil C stocks reported upon conversion of the Cerrado to cultivated land (Souza et al., 2018). Moreover, conversion of lands reduces infiltration rates, increases susceptibility of soils to erosion, and contributes significantly to biodiversity loss.
- **China:** yields of Chinese cotton are currently more than double the world average and therefore have less room for growth.
- **Sub-Saharan Africa:** Cotton is an important export crop for Sub-Saharan Africa, currently accounting for 15% of global exports. Cotton production has been increasing through area expansion. The textile and apparel industry is expected to grow in countries such as Ethiopia and Tanzania, with domestic cotton production an important part of green growth and economic development strategies.

Against this backdrop, it is critical that cotton cropping systems are carefully managed to preserve the health and productivity of the land. It is an important source of income for millions of farmers and empowers households and communities to meet their food security and nutritional needs.

1.7 Improving soil health in cotton-based systems

1.7.1 Growth of sustainable cotton initiatives

In response to the negative environmental impact of chemical-intensive cotton production, cotton grown to sustainable or organic agricultural standards and programs have been steadily increasing since 2010 (see Table 4).

Table 4. Growth of sustainable and organic cotton production since 2010

Year	Total production (1000t)	Sustainable and organic cotton production (1000t)	% share / total world production
2010	25 869	185	1%
2011	27 856	578	2%
2012	27 079	1 289	5%
2013	26 225	1 490	6%
2014	26 233	2 465	9%
2015	21 640	3 211	15%
2016	23 196	3 609	16%
2017	26 798	5 375	20%
2018	25 972	6 400	25%

Source: ICAC (2021)

These include the following:

- ABRAPA (Responsible Brazilian Cotton)
- BASF e3
- Better Cotton
- bioRe
- Cleaner Cotton
- Cotton made in Africa (CmiA)
- Fairtrade Organic
- Field to Market
- ISCC Certified
- *my*BMP
- Global Organic Textile Standard (GOTS) organic cotton
- Organic Content Standard (OCS) organic cotton
- Recycled cotton

- REEL Cotton
- Regenerative Organic Certified (ROC)
- Transitional Cotton
- US Cotton Trust Protocol

Figure 7. Logos of sustainable cotton initiatives. *Source: Textile Exchange (2021a)*

Among these standards and initiatives, agroecological practices are required to a varying degree. Some focus on prohibiting harmful practices, some require adoption of best management practices, while others focus on more efficient use of resources. They also vary in their social criteria, such as requirements for fair wages and safe working conditions. Better Cotton is the largest initiative with Better Cotton now grown in 24 countries, by 2.2 million farmers, and accounting for 20% of global cotton production (Better Cotton, 2021).

According to Textile Exchange's Sustainable Cotton Challenge, where signatories commit to sourcing 100% of their cotton from the above recognized initiatives by 2025, 162 brands and retailers have signed the pledge. While the signatories have been demonstrating progress toward meeting their targets, the market share of the members only represents approximately 7% of the total cotton market (Textile Exchange, 2021a).

In the case of organic certifications and standards, farmers are limited to use approved chemicals only in a highly regulated farming approach. Production of certified organic cotton started in 1989/1990 and around 30 countries currently produce organic cotton. While organic cotton has long been advocated for by fashion brands and consumers, it only constitutes 0.95% of total cotton production (Textile Exchange, 2021b). Organic farming has typically been regulated as a technical list of 'what not to do', especially regarding the use of synthetic pesticides, replacing them with natural inputs or organic pesticides. The latter includes zinc and copper oxides that have since been criticized for their harmful impact on biodiversity (Kuehne et al., 2017). While organic methods generally enhance soil health compared to conventional practices by replacing chemicals inputs with natural ones, it can overlook other best management practices that improve soil fertility and physical structure. For example, restrictions on herbicide use can encourage farmers to rely on tillage for weed control which destroys soil structure and increases loss of soil from erosion. The latest 'Organic 3.0' strategy aims to change this by becoming less prescriptive and moving towards more outcomes-based regulations that are more adaptable to local contexts (Shreefel et al., 2020).

1.7.2. Context-specific and scale-appropriate approaches

When it comes to sustainability in cotton production, standards-based approaches currently dominate the landscape, as demonstrated in the previous section. These approaches prohibit or promote certain agricultural practices that are considered less harmful than conventional methods. While CA is more of a practice-based than outcomes-based approach, it should not be seen as a 'one size fits all' approach.

The three principles of minimal disturbance, permanent soil cover, and crop diversity are at the core of CA, but farmers can use an array of practices under each principle which can be

applied in a variety of combinations to meet their needs and according to their specific context. This is important as agricultural management impacts on soil properties, such as tillage on SOM, vary by soil type, cropping system, type of crop residue, residue management and climatic conditions (Wright et al., 2005, Paustian et al., 1997). Different crops in cropping systems have different soil water contents, weed control, aeration and fertilizer use requirements. Soils differ in inherent physical, chemical, and mineralogical characteristics and therefore requires site-specific management practices.

This flexibility and adaptability means that CA has potential for all agro-ecological systems and farm sizes (Farooq and Siddique, 2015). While this can make it difficult to qualify full adoption of CA, the benefit is that CA can be tailored or used in combination with other technologies according to cropping system, agro-climatic zone, soil type, and other contextual factors. This paper reports the results of a project to review cotton-related CA research to date so that it can be used to inform context-specific management plans and initiatives.

CHAPTER 2

METHODOLOGY

2.1 Data collection

An extensive online literature search was conducted to collect field studies on CA practices in cotton-based cropping systems using *Google Scholar, Scopus, Web of Science,* the Cornell University Conservation Agriculture Research Database and *SoilHealthDB* created by Jian et al. (2020). The keywords used in searching the peer-reviewed literature were “cotton”, “Conservation Agriculture”, “soil health”, “soil quality”, “no-till”, “yield”, “cover crop”, “rotation”, “carbon sequestration”. Papers from conferences, theses and dissertations were not included. All publication dates and languages were included, but papers published in English were prioritized.

The studies were selected based on the following criteria:

1. Experimental trials were conducted at a research station or on-farm.
2. Publications compared controls (eg. conventional management practices) and treatments (eg. CA practices).
3. The location of the experiment was provided.
4. Publications measured at least one soil health indicator or cotton yield.

2.2 Database creation

Information was extracted from publications and integrated into a new database named *DG Cotton and Soils DB*. The database matrix contains the following fields:

- Author(s), title of paper, year of publication
- Sampling year(s), duration of trials
- Site information, country, region, coordinates
- Climate region (IPCC classification)
- Cotton species

- Cropping system
- Soil type, texture, and order
- Treatments and CA practices (reduced tillage (RT), cover crops (CC), and crop rotation (CR))
- Physical, chemical, biological soil health indicators measured
- Soil sampling depth
- Outcomes: impact on soil health indicators
- Outcomes: impact on crop yields (seed cotton yield or lint yield)

If latitude and longitude were not reported, the coordinates were approximated by entering the site name into Google Maps. Climate region and soil order were assigned to each study by using QGIS.

2.3 Data processing

The studies included in the database often reported soil attribute and/or climate information for the experiment sites, however, they often used different classification schemes. To make these pieces of data more comparable, the database was associated with external data sources.

The IPCC climate region classification was used. The first step to integrating climate region into the database was to construct the IPCC climate map in QGIS, which is detailed in the next section. Coordinates provided by each paper were used as vector data and used to extract information from the IPCC climate zone map.

The twelve orders of soil taxonomy were used as the soil classification scheme. Soil order was directly included in the database if reported in the publication or deduced from the soil series. If neither were provided, soil order was identified by extracting data from the USDA-NRCS soil regions map, using the coordinates of the experiment sites as point data.

2.4 GIS map production

Table 5 summarizes the types of GIS data and data sources that were used for this project, organized according to the input layer it relates to.

Table 5. Details of data types and sources

Input layer	Data type	Source	Details
1 – Climate regions	Near surface temperature	University of East Anglia (UEA) Climatic Research Unit (CRU) database	netCDF, 2011-2020 monthly data, 120 bands (12 months x 10 years)
	Ground frost frequency		netCDF, 2011-2020 monthly data, 120 bands (12 months x 10 years)
	Precipitation		netCDF, 2011-2020 monthly data, 120 bands (12 months x 10 years)
	Potential Evapotranspiration		netCDF, 2011-2020 monthly data, 120 bands (12 months x 10 years)
	Global digital elevation	GLOBE (Global Land One-kilometer Base Elevation)	30-arc-second (1 km) global digital elevation data set
2 – Soil regions	Global soil regions	USDA NRCS	geoTIFF, soil taxonomy sub-orders
3 – Cotton production	Global cotton production (tons)	MapSPAM 2010 v2.0 Global Data	geoTIFF

The global climate map was created in QGIS using all 2011-2020 data files from the University of East Anglia CRU database, and global digital elevation data from GLOBE (2020), and by following the IPCC classification scheme for climate regions shown in Figure 8. The final climate region map is shown in Figure 9.

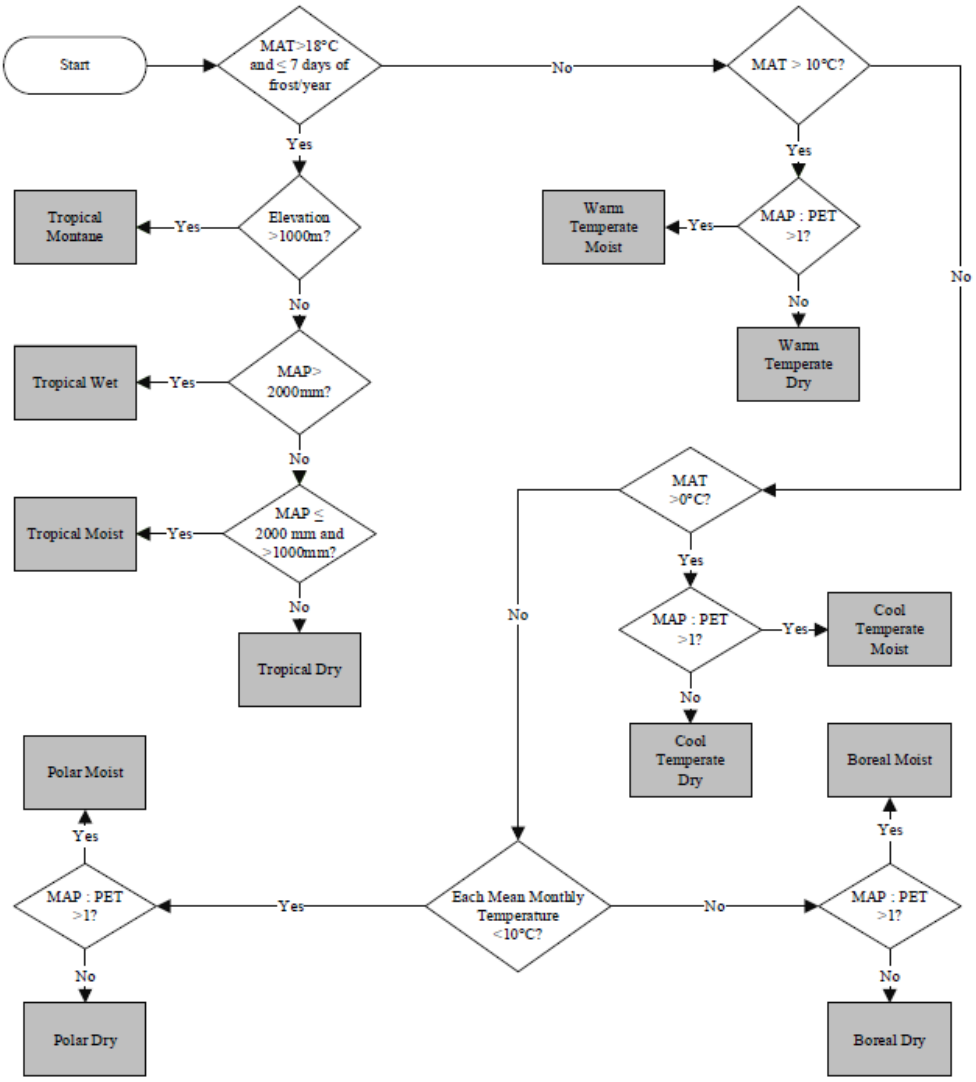

Figure 8: IPCC classification scheme for default climate regions. *Source: Reddy et al. (2019)*

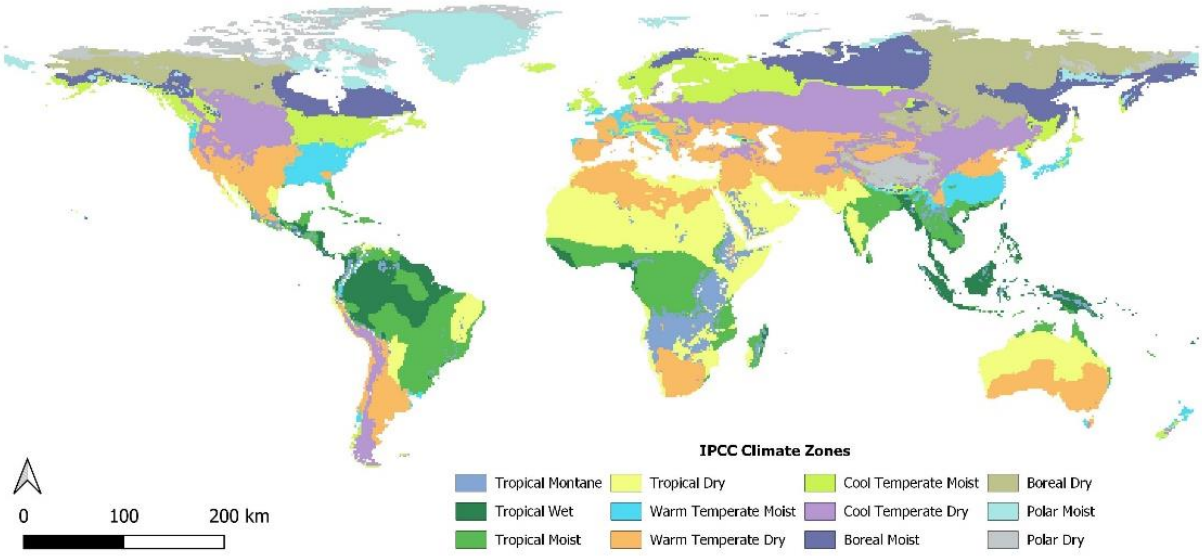

Figure 9. Final map and input layer of global climate regions

The soil order map was also constructed in QGIS by importing soil taxonomy sub-orders from USDA-NRCS (2022) and remapping the data to the level of soil orders using the "*Reclassify*" QGIS tool. Figure 10 shows the final map that was used as an input layer for the analysis.

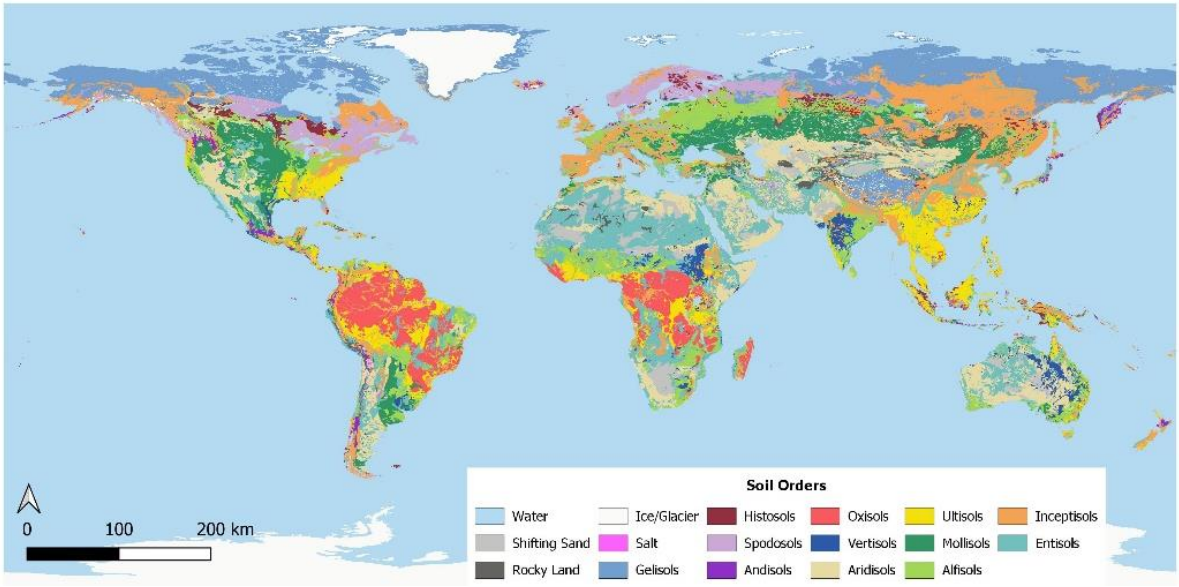

Figure 10. Final map and input layer of global soil regions

The QGIS "*Sample raster values*" tool was used to extract climate zone and soil region data from the maps using the longitude and latitude of each experiment site.

2.5 Data analysis

All analysis was conducted using QGIS Geoprocessing tools and Microsoft Excel.

CHAPTER 3

RESULTS AND DISCUSSION

3.1 Overview of the database

A total of 150 publications were collected, of which 134 publications met the assessment criteria for integration into the database and subsequent analysis. Accounting for publications that involved multiple experimentation sites and removing duplicates of research stations where multiple experiments took place, a unique list of 86 total experiment sites were recorded.

The number of studies performed in the United States was the highest (67 publications), followed by India (17), Australia (9), Pakistan (7), China (6), Turkey (6), Brazil (5), Uzbekistan (3), Spain (3), Cameroon (2), Zambia (2), Egypt (2), Zimbabwe (1), Benin (1), Burkina Faso (1), Sudan (1) and Iran (1). The concentration of cotton-related CA studies in the US both reflects the importance of the US as a cotton producer and exporter, the large amount of investment in scientific research, but also the history and growing interest in CA-based practices. For example, no-till production of cotton in the US began to gain momentum in the 1980s, starting with the highly erodible loess deposits east of the Mississippi Delta (Raper et al., 2020). Cotton is grown in 17 different states, covering a wide range of agro-ecological zones within one country.

The duration of the trials in 92 out of 134 publications was less than 6 years. 14 were between 6-10 years, and 27 trials were 10 years or longer. Of the studies that were 10 years or longer, 78% were conducted in the United States.

Some patterns in research by country were identified. For example, experiments in China had a strong focus on soil carbon sequestration, agricultural GHG emissions, and irrigation, cover crops and mulching as practices. In contrast, cotton-related research in Turkey and Egypt

focused more on identifying improved cultivars, or suitability for CA with GM seeds, rather than soil health.

In terms of temporal analysis, a cyclical pattern was observed with no clear trend in total number of publications over time (see Figure 11). 2021 had the highest number of CA publications of all years.

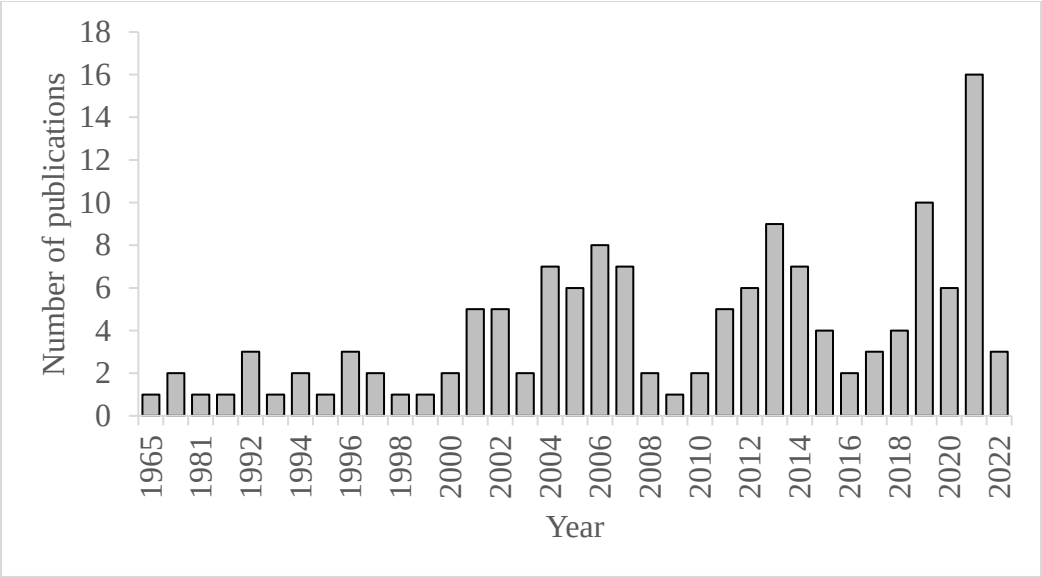

Figure 11. Number of published articles used in the database according to the year of publication

A summary of results by country, cropping systems, CA practices covered, soil health indicators measured can be found in Table 6.

Table 6. Summary of database results

	USA	India	Australia	Pakistan	Brazil	China	Turkey	Uzbekistan	Spain	Cameroon	Zambia	Egypt	Zimbabwe	Benin	Burkina Faso	Sudan	Iran
Cropping systems																	
Continuous cotton	46	7	3	0	0	5	3	0	0	0	0	1	0	0	0	0	0
Cotton-wheat	3	7	1	6	0	1	2	1	0	0	0	0	0	0	0	0	1
Cotton-maize	6	0	0	0	0	0	0	0	3	0	2	0	0	1	1	0	0
Other	18	2	5	1	6	0	1	2	0	3	0	1	1	0	0	1	0
CA practices																	
RT	19	11	2	6	1	1	5	2	3	0	1	2	0	1	1	1	1
RT-CC	33	2	0	1	2	0	1	0	0	3	0	0	1	0	0	0	0
CC	8	2	1	0	0	3	0	0	0	0	0	0	0	0	0	0	0
RT-CR	2	0	6	0	1	0	0	1	0	0	0	0	0	0	0	0	0
RT-CC-CR	5	1	0	0	2	0	0	0	0	0	1	0	0	0	0	0	0
CC-CR	5	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
CR	1	1	0	0	0	2	0	0	0	0	0	0	0	0	0	0	0
SH indicators																	
Ph	11	1	2	0	1	0	0	0	1	0	0	2	0	0	0	1	1
Ch	7	3	1	1	3	4	0	1	0	0	0	0	0	0	0	0	0
B	2	1	0	0	0	0	0	0	0	2	0	0	0	0	0	0	0
PhCh	16	3	3	3	2	1	1	1	1	0	1	0	0	0	0	0	0
PhB	2	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0	0
ChB	7	0	0	0	0	0	0	0	1	0	0	0	0	0	0	0	0
PhChB	6	1	2	1	0	0	0	0	0	0	1	0	0	0	0	0	0
Duration																	
1-2	13	6	1	5	2	3	5	1	1	0	0	2	0	1	1	1	1
3-5	33	8	3	2	0	2	1	1	2	2	1	0	1	0	0	0	0
6-9	5	0	4	0	2	1	0	1	0	1	0	0	0	0	0	0	0
10+	22	3	1	0	2	0	0	0	0	0	1	0	0	0	0	0	0

CA practices*: RT, Reduced Tillage; CC, Cover Crops; CR, Crop Rotation.*
SH indicators*: Ph, Physical; Ch, Chemical; B, Biological.*

3.2 Cropping systems

The cropping systems represented in the database reflect common cotton-based cropping systems in each country. Monoculture cotton systems are prevalent in the US and NW China, often leaving fields fallow in the winter. On the other hand, cotton-wheat is the dominant cotton-based cropping system in Pakistan, northern India (Das et al., 2004), and Uzbekistan, with

cotton-wheat-rice also popular in Uzbekistan (Kahriz et al., 2020). Other important cropping systems in Pakistan are cotton-chickpea, cotton-fodder and cotton-fallow (Ali et al., 2020). In Turkey, the predominant cropping system in the major cotton growing areas is cotton-cotton double cropping, though in other areas cotton-wheat and cotton-maize are common (Basal et al., 2020). Double cropping is becoming more common in Brazil, where the rainfall regime in the Mato Grasso, the main state producing cotton in the Cerrado, favors cotton as second crop (Hoffmann et al., 2020). Cotton is generally planted after soybean, and sometimes common beans, and harvested during the same crop season. In Bahia, cotton is more commonly planted after maize or maize intercropped with *Urochloa ruzizienzis*.

3.3 Conservation Agriculture practices

Figure 12 shows the distribution of cotton production and distribution of experiments by CA practice.

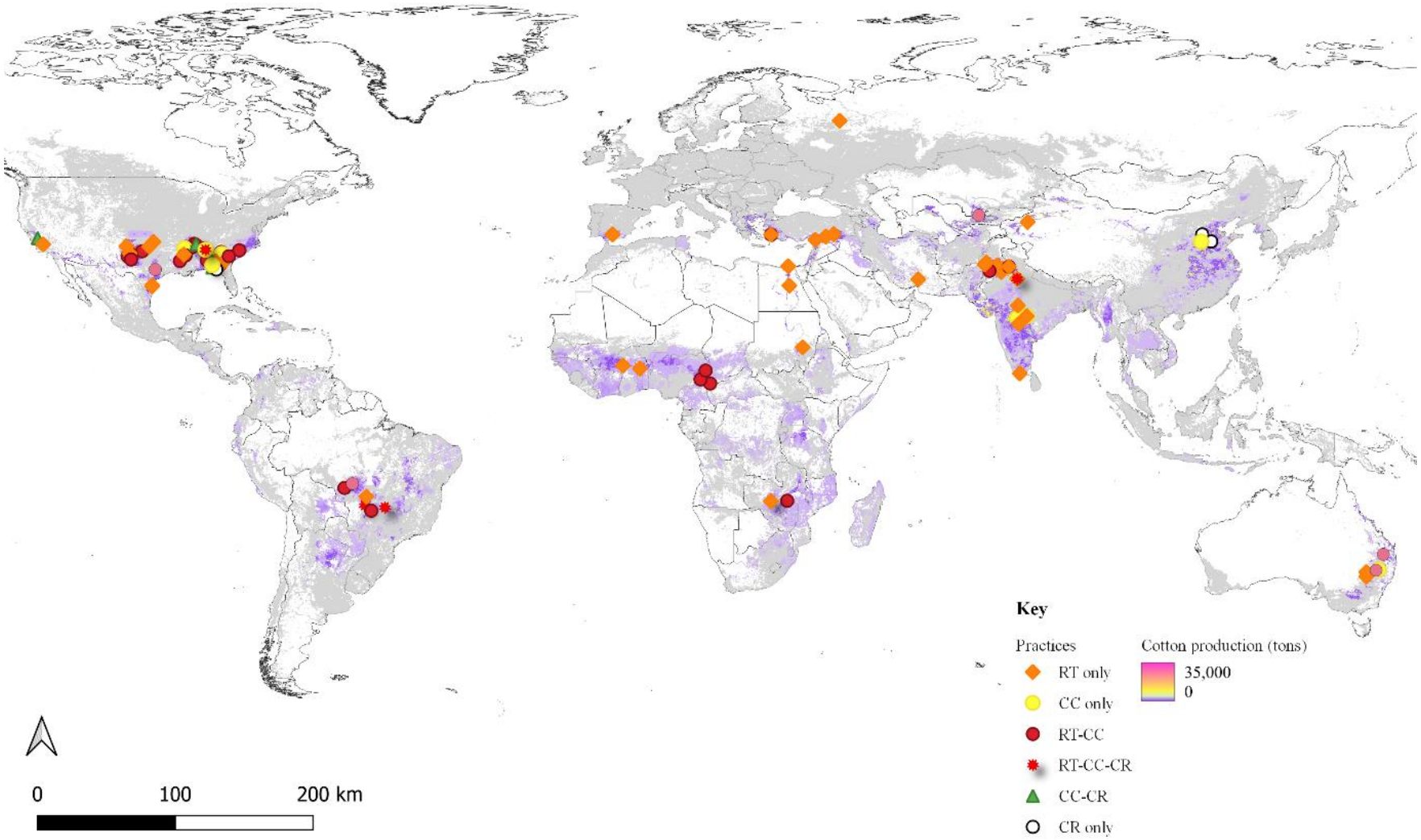

Figure 12. Map showing cotton production (tons), location of CA experiments, and CA practices assessed

40% of publications focused solely on reduced tillage practices, which includes no-till. The next most common was the combination of reduced tillage practices and cover crops (30%) followed by solely cover cropping (9%), reduced tillage combined with crop rotations (7%), all three CA principles (7%), cover cropping and crop rotations (4%) and solely crop rotations (3%). Within these three categories of practices, there was huge diversity (see Table 7).

Table 7. Details of CA practices covered in the database

Category of CA practice	Examples used in literature	
Reduced tillage	• No-till / Zero tillage • Minimal tillage • Reduced tillage • Strip tillage • Deep tillage	• In-row subsoiling • Chisel tillage • Mulch tillage • Ridge planting • Permanent beds
Cover crops	• Cereal rye • Winter wheat • Hairy vetch • Crimson clover • Balansa clover • Cowpea • Austrian winter pea • Brown/white mustard	• Sunn hemp • Oat • Radish • Brachiaria • February orchid • Sorghum sudangrass • Barley • Pigeonpea
Crop rotation	• Maize • Soybean • Wheat • Sorghum	• Canola • Millet • Peanut • Tomato

3.4 Soil health indicators

Of the publications that did assess impacts on soil health, only 13 measured soil health comprehensively with physical, chemical, and biological indicators included. Physical and chemical soil properties dominated, with bulk density and SOC the most commonly chosen indicators of soil health. Water-related indicators such as soil moisture content, water-use efficiency and infiltration were also common. These are important considerations for cotton,

which is known for its intensive consumption of water, and for improving insurance against drought in the face of climate change.

Only 24 publications considered biological indicators. 17 of these took place in the US, with the remaining in India (2), Australia (2), Pakistan (1), Cameroon (1), Spain (1), and Zimbabwe (1). 75% of these papers were published after 2004.

58 number of publications focused on impacts of CA practices on both soil properties and yield. Of these, only 5 publications took a comprehensive approach to soil health assessment, measuring physical, chemical, and biological indicators. This highlights a need for more research that uses a comprehensive definition of soil health and measures the effect of management practices on both soil health and crop growth characteristics.

3.5 Yield and fiber quality

Lack of information on the effects and interactions of CA-based practices on yield is often cited as a factor hindering its adoption among farmers (Farooq and Siddique, 2015). 34 studies only measured effect on cotton yield, and other crop growth characteristics in some cases, with an absence of soil health indicators.

16 papers measured the effects of CA treatments on fiber quality, with the vast majority reporting no significant differences between treatments (Blaise, 2011; Zhang et al., 2007; Blaise, 2006; Unay et al., 2005; Yalcin et al., 2005; Boquet et al., 2004; Hulugalle et al., 2004; Pettigrew and Jones, 2001). Hulugalle et al. (1997) observed fiber quality improvements with minimal tillage, and Khan et al. (2021) saw increased fiber length, strength and micronaire under no-till compared with minimum tillage. On the other hand, Khan et al. (2014) and Usman et al. (2014) found improved fiber quality with reduced tillage compared to no-till. Constable et al. (1992) found that micronaire reduced slightly with crop rotation.

3.6 Climate zones

Using the unique list of experiment sites, Table 8 shows the distribution of cotton-related CA research by climate zone compared with the distribution of cotton production.

Table 8. Comparison table of cotton production and CA research by IPCC classified climate zone

Climate zone	% Cotton production	% CA research
Tropical Montane	8%	1%
Tropical Wet	3%	1%
Tropical Moist	33%	15%
Tropical Dry	25%	11%
Warm Temperate Moist	9%	25%
Warm Temperate Dry	21%	44%
Cool Temperate Moist	0.04%	1%
Cool Temperate Dry	1%	1%
Boreal Moist	0%	0%
Boreal Dry	0%	0%
Polar Moist	0%	0%
Polar Dry	0%	0%

According to the QGIS analysis using cotton production data and IPCC classification of climate regions, cotton is grown in 8 different climate zones. The sites in the database covered all 8 climate regions, though the distribution was not as representative. Despite 69% of cotton production being in tropical climates, only 25% of CA research was conducted in tropical climates. 56% of experiments were in dry climates, often assessing the ability of CA practices to improve water retention capacity of soils or reduce wind erosion. 69% of research took place in warm temperate regions, where 30% of cotton production is. The reason for this is the large number of sites in the US, especially Texas and Alabama. This finding corroborates other CA reviews that found a lack of reliable information on the influence of tillage, residue management

and crop rotation on soil health indicators (Govaerts et al., 2009). For example, Somasundaram et al. (2020) discuss the concentration of no-till research in temperate countries such as the US, South America and Europe, and temperate-tropical countries such as Australia and China. However, the potential for soil health restoration in tropical regions is high where the temperature regimes and moist conditions favor certain soil processes. In an assessment of agricultural management impacts on SOC storage under different climates, Ogle et al. (2005) found that converting from conventional tillage to zero tillage increased SOC storage in tropical moist and tropical dry climates more than temperate climates. In tropical moist climates, SOC storage increased over 20 years by a factor of 1.23 ± 0.05, corresponding to a 23% increase in SOC (Ogle et al., 2005).

Taking climate into consideration when deciding appropriate sustainable management practices to implement is incredibly important. In a global meta-analysis that surveyed 678 studies of effects of no-till cultivation, Pittelkow et al. (2015) found that in contrast to wetter production environments, no-till often either sustained or increased yields in dry climates compared to conventional tillage. Among all the crop categories and locations evaluated, no-till reduced yields by 5.1% but yields for cotton, oilseeds and legumes were not affected. This is extremely relevant for cotton, where 47% of cotton production in 2010 was estimated to grow in dry climates (see Table 8). In water-limited areas, especially without access to irrigation, improving soil water retention properties and reducing water loss through runoff are important.

A total of 69 experiments in the database were situated in arid or semi-arid climates where water conservation is a priority. CA is well known to improve water cycling and have a lot of applications in dry climates and rainfed systems where water is the limiting factor in agricultural systems.

However, not all CA-based practices were found to be beneficial in dry climates. Adoption of reduced tillage and residue retention resulted in higher yields compared to conventional tillage by Das et al. (2014) and with minimum tillage and rotation with wheat by Hulugalle et al. (1997) but planting cover crops reduced yields compared to no cover crops by Li et al. (2013). This will be discussed further in Section 3.9.

3.7 Effects on SOC

35 studies (26%) of the publications measured SOC. Of these, 12 measured SOC beyond the 0-30cm soil depth ie. subsurface soil layers. In most cases, CA practices resulted in higher SOC content in surface layers due to increase C input, especially when high residue generating crop species were integrated into the system (Wang et al., 2021; Novak et al., 2020; Burke et al., 2019; Gamble et al., 2019; Somasundaram et al., 2019; Lewis et al., 2018; Reddy et al., 2017; Cid et al., 2014; Yang et al., 2014; Zablotowicz et al., 2011; Jalota et al., 2008; Sainju et al., 2006; Terra et al., 2005; Wright et al., 2005; Blaise and Ravindran et al., 2003; Truman et al., 2003; Mitchell and Entry, 1998; Salinas-Garcia et al., 1997). However, Terra et al. (2005) speculated that SOC increases observed could have corresponded to increases is more labile SOC fractions rather than more recalcitrant soil C pools that persist in soils for longer. These recalcitrant pools tend to be less decomposable material and are physically protected from microbial activity. Measuring POXC and well as SOC is a useful way of measuring these two different C pools, where POXC measures active carbon that is much more sensitive to management changes and reflect the C that is available to microbes.

Furthermore, rates of SOC storage under zero tillage compared to conventional tillage can be overstated if the entire plow depth is not considered (VandenBygaart and Angers, 2006). In experiments that sampled deeper layers of soils, it was often the case that despite increases in

SOC in surface layers (0-5cm), SOC stocks were comparable between CA and conventional treatments in the 0-30cm layer and deeper (DeLaune et al., 2019; Das et al., 2013; Wright et al., 2005). This highlights the importance of soil sampling depth where no-till and residue retention often changes the distribution of SOC rather than total SOC stock in the short-term, with higher SOC in the surface layers where the residues stay concentrated rather than in deeper layers where residue is incorporated through tillage. Nevertheless, Ferreira et al. (2020) reported an increase in SOC stocks in the 31-40cm layer when *U. ruziziensis* was included as a cover crop in the rotation with cotton, due its deep roots.

In a long-term trial, Novak et al. (2020) studied the effect of 37 years of conservation tillage in loamy sand soils in the SE US Coastal Plain. The authors reported an exponential increase in SOC within the top 5cm depth between 1978-2016 which then plateaued. This suggests a SOC saturation point, beyond which additional topsoil SOC increases with the same management practices are limited. Outside of cotton-based systems, other studies of reduced tillage impact on SOC have found that a new steady state SOC level is reached between 21 years (West and Six, 2007) and 30 years (Meurer et al., 2018) of continuous reduced tillage, with no further increase in SOC beyond this point using the same practices.

3.8 Soil orders

Cotton is grown on a wide range of soils across the world. Similar to the climate zone coverage, sites in the database covered all 8 soil orders where cotton production is estimated to grow. Table 9 shows the results.

Table 9. Comparison table of cotton production and CA research by soil order

Soil order	% Cotton production	% CA research
Gelisols	0%	0%
Histosols	0%	0%
Spodosols	0%	0%
Andisols	0%	0%
Oxisols	10%	9%
Vertisols	7%	14%
Aridisols	9%	7%
Ultisols	16%	18%
Mollisols	4%	11%
Alfisols	22%	18%
Inceptisols	13%	7%
Entisols	19%	16%

The distribution of the CA research was more representative of cotton production distribution across the soil orders, with the largest number of experiments located on Ultisols, Alfisols and Entisols. 9 papers specifically looked at the effects of CA practices on cotton grown in Vertisols, especially in Australia where majority of cotton production is grown in Vertisols. Vertisols have high clay content and characteristically shrink and swell as it goes through drying and wetting cycles. Cracks develop when these soils dry, allowing water to enter the soil. However, when the soil is wet and starts to absorb water, the cracks close which restricts water infiltration. High clay content soils are particularly prone to waterlogging after rainfall or irrigation, increased vulnerability to disease, and suffer compaction from traffic or tillage of wet soil due to its plastic nature. Smith (1995) argue that clay soils are not well suited for dryland production of cotton and produced less yield than coarser textured soils due to the slow movement of water through soil resulting in poor drainage and infiltration. This makes it difficult for plants to access soil water as well as possible surface runoff and water erosion. Soils can

become waterlogged, starving plants and aerobic soil microorganisms of oxygen. High clay content soils therefore must be carefully managed to have good soil structure.

Ultisols are clay-rich soils that are found in warm and humid climates. They tend to be acidic and low fertility soils due to intense weathering. Ultisols are made agriculturally productive through application of lime and other practices that build soil fertility. Alfisols, on the other hand, have very different characteristics and therefore require different management approaches. Alfisols formed under forests, have high native fertility and are moderately leached soils. However, they have several characteristics that make management difficult, including low water holding capacity, high soil strength when dry, and poor surface soil stability which can make them vulnerable to soil degradation from intensive tillage practices (Cogle et al., 2002). Mollisols are considered to be among the most fertile soils due to clay and organic matter content. These mineral soils developed under grassland, which have extensive fibrous root systems. Entisols and Inceptisols are young soils without much horizon development. These tend to be sandier soils with parent materials that are more resistant to weathering or are found in colder climates where soil profile development is slower. Govaerts et al. (2009) propose that depleted old soils have more potential to sequester carbon compared to young soils rich in carbon. The productivity of these younger soils is much more varied and depends on location and history of management.

In tropical regions, where a significant proportion of cotton production is, soil mineralogy and texture have a strong influence in C storage (dos Santos et al., 2020). Sandy soils have low fertility, low water holding capacity, low CEC and are prone to higher C loss through lower aggregation and surface area of sand particles. In their study of cotton grown in sandy Entisols in Mato Grosso, dos Santos et al. (2020) recommend crop rotation with a species that has high

biomass production, to protect soil against high temperatures and impacts of raindrops, and that produces residues with a low decomposition rate given the hot and wet climate.

Where increasing water retention is the main objective, a positive correlation between increasing SOM and available water capacity has been documented for sandy and silty soils than fine-textured soils (Al-Kaisi and Lal, 2017).

3.9 Win-win cases

This section reviews 40 publications that reported that CA-based practices improved soil health indicators without compromising cotton yields, or even increased yields, therefore recommending CA adoption in the region where the studies are based. These are defined as 'win-win' cases.

Increases in yields ranged from 1%-114% compared to the conventional control treatment. Some reported that combining multiple CA practices achieved the best results, such as reduced tillage and cover crops (Nouri et al., 2021, 2019; Ferreira et al., 2020; Blaise, 2011; Boquet et al., 2004; Reddy et al., 2004; Schwab et al., 2002; Raper et al., 2000), or reduced tillage and crop rotations (dos Santos et al., 2020; Khaitov and Allanov, 2014; Hulugalle et al., 2004; Bordovsky et al., 1994), compared to reduced tillage alone. Among studies of conservation tillage, there were cases where reduced tillage achieved better results than no-till especially regarding soil moisture content and infiltration (Khan et al., 2014; Usman et al., 2014, 2013; Blaise and Ravindran, 2003).

Cover crops were found to increase microbial activity resulting in greater soil C and N storage (Mbuthia et al., 2015), increase root channels for preferential water flow and transport of soluble salts (Burke et al., 2022), and suppress weeds (Blaise, 2011; Norsworthy et al., 2011; Blaise, 2006). Some studies reported positive results using multi-species cover crop mixtures

compared to single species (Sainju et al., 2006a; 2006b; Keisling et al., 1994), while others achieved better results with single cover crop species (Burke et al., 2022, 2019; Bhaskar et al., 2018).

Regarding specific cover crop species, several researchers found that cereal rye cover crops (Sainju et al., 2006; Raper et al., 2000) or cereal rye-containing mixtures (Keisling et al., 1994) outperformed other species and CA practices largely to its biomass generation. Others found legume cover crops such as hairy vetch gave higher yields (Nouri et al., 2021, 2019; Rochester and Peoples, 2005) or higher soil quality scores (Mbuthia et al., 2015) than cereal crops. In an experiment involving 12 legume cover crop species in cotton-wheat cropping systems, Rochester and Peoples (2005) found that when vetch was grown after wheat, it added nearly 230 $kgNha^{-1}$ when incorporated as green manure, which was sufficient for cotton requirements therefore displacing all N fertilizer application. This has the co-benefits of reducing GHG emissions, reduced likelihood of N leaching, protection of soil microorganisms, and reliance on expensive fertilizers. Locke et al. (2012) found that different cover crop species had varying effects on different soil health indicators. For example, clover cover crop treatments had the highest TN and aggregate stability, whereas mycorrhizal populations were greatest under cereal rye. The underscores the importance of comprehensive soil health assessments to target identification of the best cover crop species for addressing specific constraints. Taking into account the cost of inputs and economic returns, Schomberg et al. (2006) recommended black oat as cover crop species for cotton cropping systems in the SE US Coastal Plain over cereal rye, oilseed radish, hairy vetch and Austrian winter pea.

Some authors reported that crop rotations were more effective in improving soil properties or yields than cover crops (Ashworth et al., 2016) or compared to reduced tillage (dos Santos et al.,

2020). However, when yields of all crops in the rotation were measured, there were cases where cotton yields increased under CA treatments but not for the other crops (Wright et al., 2005). Devkota et al (2013) found the opposite effect, where CA practices had more positive effects on yields of wheat and maize than cotton in irrigated arid lands that had been previously mono-cropped with cotton under heavy mechanization for 20 years. Collaboration between food and fashion sectors will be critical to developing optimal approaches for meeting farmers' objectives such as food security and cash crop income.

Positive effects of CA-based practices were often found to be enhanced when combined with manure amendments such as poultry litter (Sainju et al., 2008; Terra et al., 2005; Reddy et al., 2004; Endale et al., 2002; Nyakatawa et al., 2001). Nyakatawa et al. (2001) tested the use of no-till, mulch till, cover cropping and poultry litter, finding that the surface application of poultry litter increased SOM by 55-80% and that the soil in the poultry litter plots had more N compared to ammonium nitrate plots.

3.10 Negative results

Major challenges adopting CA practices are the prevalence of weeds, pests, diseases, lack of suitable systems to manage residues, and availability of equipment. 7 papers in the database reported negative impacts of reduced tillage on soil health indicators, mostly due to increased soil compaction (Cid et al., 2014; Hulme et al., 1992; Wild et al., 1992; Porterfield and Davidson, 1974). This may inhibit seedling emergence and root growth over time. Increased soil compaction was sometimes reported in a few other cases alongside the improvement of other soil health indicators (Nouri et al., 2019; Somasundaram et al., 2019; Hullugalle et al., 1997; Salinas-Garcia et al., 1997). Occasional tillage may be required to relieve compaction issues and sustain the benefits of long-term no-till. In a review of historical management of cotton production

systems in North Carolina,Franzluebbers et al. (2021) found that intermittent use of tillage was an impediment to sustained SOC accumulation. This contradicts other studies that found that occasional tillage does not decrease SOC or yields compared to strict no-till (Blanco-Canqui and Wortmann, 2020). The frequency of tillage was not mentioned in Franzluebbers et al. (2021) but could have been a factor affecting SOC accumulation.

Negative outcomes related to cover cropping was often to do with certain species outcompeting cotton such as sorghum sudangrass (Bhaskar et al., 2018), allelopathy (Li et al., 2013), or pests (Buntin et al., 2002). Li et al. (2013) detected higher concentrations of allelochemicals in soils where wheat or cereal rye cover crops grew, resulting in lower cotton growth and yield compared to cotton planted with no cover crop. Norsworthy et al. (2011) found a similar allelopathic effect on cotton when following turnip. While allelopathic properties of cover crops are often considered a benefit for weed management, care must be taken with cover crop species selection and timing of termination to ensure subsequent cash crops are not affected. In an experiment with canola as the cover crop, Buntin et al. (2002) reported an increase in cotton seedling infection by *Rhizoctonia solani* following canola compared to wheat or the fallow control, though both cover crop species reduced cotton aphids and thrips compared to fallow.

Baumhardt and Lascano (1999) assessed the impact of cotton and winter wheat intercropping in the Texas South Plains, a dryland environment, and found superior crop establishment in the continuous cotton plots compared to wheat cover crop plots due to increased water use for wheat growth. This competition for water resources in water-constrained environments, either in semi-arid or arid climates or where local water availability is increasingly scarce, and in rainfed cropping systems is a commonly cited concern of growers regarding the use of cover crops.

Cover crop use of stored soil water during winter months can have negative impacts on the subsequent cotton crop (Bhaskar et al., 2018) and crop establishment and biomass generation is more challenging. Soil attributes can play an important role, where CA can build the water retention capacity of sandy soils in dry climates. Better results in sandy soils were achieved with residue retention (Thierfelder and Wall, 2010) or no-till (DeLaune et al., 2019) than cover crop usage alone.

High clay content soils retain more soil moisture, which is beneficial during drought years, but they can also suffer from poor drainage. The findings of Rawls et al. (2003) demonstrated increased organic C content had negative effects on soil water retention of fine-textured soils when soils had low C contents to begin with, resulting in less plant available water. Poorly drained soils can have more anaerobic micro-sites that favor denitrification, an anaerobic microbial process that can result in the release of N_2O, a GHG that has 300 times the warming potential of CO_2. Soil amendments, such as biochar, could have better applications for improving porosity and water infiltration. Biochar is obtained from the pyrolysis, meaning heating in a low or no oxygen environment, of organic matter such as agricultural wastes, animal manure, or wastewater sludge. Biochar is highly porous and therefore can increase pore space in soils, improving water cycling and providing a home for soil microorganisms. Experiments have shown that biochar can increase crop yields, improve soil fertility, and reduce GHG emissions (Orgiazzi et al., 2016). Additionally, biochar has been proposed as a climate mitigation solution by sequestering photosynthetically fixed C in a highly stable form (Woolf et al., 2021), where 97% of biochar can persist in soils on a centennial scale (Wang et al., 2016). However, biochar research in cotton-production systems is extremely limited, and the interaction between biochar and soil organisms are not well understood (Orgiazzi et al., 2016).

Complete elimination of soil disturbance can increase weed pressure. Under CA, weeds are normally controlled using herbicides, however increasing use of herbicides is not sustainable in the long-term. In the literature, cover crops were often used in combination with no-till to provide weed suppression benefits, but mixed results were found when legume cover crops were used. As discussed, use of cover crops may not always be beneficial in water-constrained environments. For cotton growers in the semi-arid tropics of India, Blaise and Ravindran (2003) recommend a mixture of mechanical and chemical weed control that still reduces reliance on herbicides. In another study of weed management strategies in reduced tillage cotton-wheat cropping systems in Pakistan, Usman et al. (2013) found a combination of hand weeding and Haloxyfop as post emergence alone or in combination with Lactofen were most effective at reducing weed density. More research is needed to understand the changes in weed infestation and density after long-term no-till adoption in cotton systems, as well as the effect of cover crops on weed control.

3.11 Limitations and next steps

Most of the literature in the database was published in English, meaning that relevant publications in other languages will have been missed. This could be one of the reasons why the number of papers in the database are predominantly from English-speaking countries. According to the Acclimatise (2021) report of projected impacts of climate change on cotton production by 2040, northwestern Africa, including northern Sudan and Egypt, and western and southern Asia, are projected to have the highest climate risk overall. As only one publication was found in both Sudan and Egypt, further search for existing research should start here. This review has also identified the need for more research in the tropics, where the majority of cotton production is located.

All but three publications in the database used upland cotton (*Gossypium hirsutum,* L.). The only papers that used alternative species were Karishma et al. (2019), Blaise et al. (2006), Blaise (2006) that used *Gossypium arboreum* L., which has a long history of cultivation in India and is still grown in the states of Punjab, Haryana, and Rajasthan in northern India (Dagaonkar et al., 2003). While there is a lot of diversity, some *G. arboreum* varieties are more tolerant to drought, salinity and resistant to sucking pests, cotton leaf curl virus, nematodes, and root rot (Tahir et al., 2021). No publications studied the effects of CA practices on *Gossypium barbadense* L., extra-long staple cotton, despite being an important economic crop in countries such as the US and Egypt, and an important type of cotton for home textiles and more luxurious cotton products. *Gossypium herbaceum* L. was also not used in any of the experiments. Unlike the other three common species of cotton, *G. herbaceum* is grown as a perennial shrub in the semi-arid regions of sub-Saharan Africa and Arabia. Perennials are much better at conserving soil health and preventing erosion. By not removing them every year, perennial crops tend to develop deeper and denser root systems that improve soil structure, and the more permanent cover helps to prevent erosion. Cotton has an indeterminate growth habit, meaning it can grow for as long as it has access to the necessary resources, but is almost always cultivated as annuals. Despite being grown at a smaller scale, more research into these other cultivatable cotton species and other wild cotton varieties would be beneficial for the industry, especially as they may have more desirable traits in more adverse conditions and on more marginal lands.

It has been demonstrated that there is huge diversity in the cotton-cased CA literature regarding practices (both CA practices and other variables such as intra-row spacing, N application rate, application of other amendments), soil health indicators, and length of trials. The suggested next step for this research is to statistically assess the relationship between

specific CA practices and soil health outcomes, by climate and soil type. This would help to determine under what site and soil conditions these soil conservation practices are most successful in simultaneously improving soil health, cotton yields, and protecting cotton supply chains. This review suggests that the greatest benefits of CA-based management practices are in contexts when water is a limiting factor to production. However, more quantitative research is required to demonstrate exactly which practices work best under different conditions.

CHAPTER 4

LESSONS FOR INDUSTRY

4.1 Location matters: soil properties and climate factors

The location of CA research found in this review and analysis of 'win-win' results indicate that there are promising opportunities for application of CA practices to improve soil health and crop productivity in low rainfall conditions due to the advantages of the practices for soil water dynamics, especially in sandy soils. Furthermore, improving water use efficiency has benefits in dryland cropping systems as well as reducing amount of water used for irrigation and associated emissions. This corroborates other CA reviews that argue for CA benefits in arid climates where water conservation and preserving soil health are intertwined (Lal, 2015), and where there is a trend towards more frequency drought events.

In tropical, humid cotton systems, there may be fewer opportunities for CA and greater opportunities for other sustainable agriculture approaches. Practices that increase porosity and infiltration, such as biochar, could have potential benefits. However, biochar as an option for cotton-based cropping systems has not been well-studied and would therefore require further research. In a study of 280 farms in Zambia, Gatere et al. (2013) argue for a combination of CA and precision agriculture for farmers in higher rainfall regions where crop yields were found to be more influenced by application of fertilizers and lime.

4.2 Managing expectations of change

While CA has contributed significantly to the conservation of soil resources and environmental quality around the world, there are often concerns regarding the time required to deliver sustainable agronomic benefits, namely higher yields without reliance on external inputs. In some cases, yield reductions were reported in the initial years of no-till adoption, with

sustained benefits of CA practices only achieved with continuous adoption. Hulugalle (2000) found C sequestration was highest where combined minimum tillage and crop rotation had been practiced for more than 10 years, with C sequestration declining in the first four years of the trial. Similarly, cotton yields decreased for the first three years of Nouri et al. (2020)'s no-till and cover crop trials but increased after 10 years. Aulakh et al. (2011) observed positive results from year 2, but only significant positive results from year 3. This raises important questions about how businesses, governments, NGOs, philanthropists, and the finance community can support farmers to adopt soil conservation practices in the long-term.

4.3 Context matters: socio-economic circumstances and cultural factors

4.3.1 Commercial-scale farms: challenges & opportunities

Large-scale farms with heavy machinery use can achieve substantial GHG reductions through adoption of CA practices, especially by reducing tillage. Several papers reviewed observed long-term SOC increases and overall reduction in total agricultural GHG emissions compared to conventional practices. The influence of CA on soil C stocks was variable and there were cases where soil C stocks were lower compared to conventional tillage. According to Marland et al. (2003), there are four main sources of CO_2 emissions in agriculture:

1) Plant respiration.
2) The oxidation of organic carbon in soils and crop residues.
3) The use of fossil fuels in agricultural machinery such as tractors, harvesters, and irrigation equipment.
4) The use of fossil fuels in the production of agricultural inputs such as pesticides and fertilizers. According to Lal (2004) 1 kg of N fertilizer releases 0.83-1.3 kg of CO2 in production, packaging, transport, and application.

Whilst SOC impacts may not yet be conclusive for all areas and cropping systems, the largest contribution of CA to reduce emissions from farming operations is in fact from reduced tillage and resultant decrease in combustion of fuel compared to conventional tillage (Govaerts et al., 2009). Furthermore, nutrient release from residues, improved soil fertility, and use of organic amendments can reduce fertilizer-related emissions. Reduced tillage and use of external inputs also reduces production costs, which could be a significant economic opportunity with rising fertilizer prices at the time of writing.

However, long-term continuous usage of no-till on commercial farms can lead to problems with weed control, compaction, and stratification of SOC and nutrients. In this review, Franzluebbers et al. (2021) found a negative impact of intermittent tillage on SOC. However, other studies outside of cotton-based systems have shown that occasional tillage (every 10-15 years) can address compaction problems with no effect on SOC accumulation.

4.3.2 Small-scale farms: challenges & opportunities

Farmers, especially resource-poor farmers, do not always have comparable conditions to research stations or homogenous characteristics (Chambers and Jiggins, 1986). While controlled scientific experiments are extremely valuable for isolating the impact of specific practices and processes, research stations tend to be located on uniform, flat land with productive soils.

Socio-economic aspects of farming cannot be overlooked, especially when assessing the feasibility of agricultural technologies or best management options. In Khan et al. (2018)'s research in Dera Ismail Khan, Pakistan, they noted that residue retention can be an unrealistic practice for resource-poor farmers that use residues as animal feed, bedding, or fuel. Burning residues to enhance pest control is a common practice or cultural norm in some regions (Pannell et al., 2014). Complete residue removal is, on average, 34% more costly to farmers than burning

(Ahmed et al., 2015; Prasad et al., 1999). These competing uses for residues highlight the need to consider local context and norms that affect the ease of implementation of sustainable agriculture approaches, as well as more structural or cultural reasons why certain sub-optimal management practices prevail in some regions. Given the opportunity cost of using residues as soil cover, farmers may not be willing to retain residues without economic incentives as was found by a survey of farmers in Malawi (Ward et al., 2016).

In an agronomic case study of CA adoption in maize-based smallholder systems, Thierfelder et al. (2012) found that farmers had fewer difficulties retaining crop residues and abandoning tillage, but poor market conditions that made rotations with legumes less profitable than maize. In this case, including legumes in rotations was found to improve water infiltration by 70-238%, increase SOC, macro-fauna abundance and crop productivity, but adoption of the environmentally beneficial practice was constrained by socio-economic factors. Availability of equipment is another important factor that has been found to restrict or slow the adoption of soil conservation principles, for example availability of proper seeding equipment for no-till (Gürsoy, 2012) or access to scale-appropriate farm implements for smallholder farmers Somasundaram et al. (2020). This point is expressed well by Baudron et al. (2012a):

"*the inability to anticipate the poor adoption of technologies that perform well in research stations often resides in the poor understanding of smallholders' contexts and constraints*."

The authors' assessment of CA on 195 farmer fields in Zimbabwe took a different design approach where farmers were given flexibility over nitrogen application timing and rates, planting dates, and number and dates of pesticide treatments, making these decisions based on their own judgement and access to inputs. Naudin et al. (2013) took a similar approach in their feasibility assessment of CA in north Cameroon which involved 662 plots on 243 farmers' fields.

Farmers operated relatively freely with only technical advice from technicians. This contrasts with highly controlled experiments in research stations but are more representative of typical smallholder conditions.

Baudron et al. (2012) warn that interventions which promote hegemonic policy models, with a 'one size fits all' approach, are dangerous in smallholder agriculture as they ignore the embeddedness of farming in wider socio-economic environments and overlook the diversity of existing farming practices and the rationale for using them. It is always important to first consider the suitability of the agricultural technologies being considered to the socio-economic realities of the farmers. In Baudron et al. (2012)'s survey of 176 smallholder farmers in the Zambezi Valley in Zimbabwe, lack of resources to hire labor meant that minimum tillage and mulching were ill-suited practices as they required more labor during peak periods when labor is scarce and expensive. In fact, clearing new land cost farmers less than investing in fertilizers, another factor driving agricultural extensification as opposed to intensification in the Zambezi Valley, though this depends on land pressures and soil fertility. Labor bottlenecks can delay planting and affect crop yields, contradicting the well-known strength of no-till in allowing planting well before the period that would be possible with conventional tillage. The authors also noted how certain practices carried different meanings, where having animal draught power, plows and cultivators were seen as the hallmark of a 'good farmer' whereas intercropping with legumes was associated with poverty where farmers were seen to 'make the most out of a small piece of land'.

This highlights opportunities to create more tailored solutions and there are several promising case studies. In a detailed case study of the changes of residue management in rice-wheat cropping systems in South Asia, Somasundaram et al. (2020) demonstrate how constraints

regarding lack of labor and equipment for no-till and residue retention have been partially overcome through the technical intervention of the Turbo Happy Seeder (THS), which is a tractor-mounted no-till residue management device, together with a straw management system developed by the Punjab Agricultural University called Super-SMS. These are more scale appropriate labor-saving innovations that cut and shred the previous rice straw, spread the residue, and plant the succeeding wheat crop into the residue. This simultaneous rice harvesting and sowing of wheat not only saves time, energy but also one irrigation as the residual moisture from the rice fields is used instead. Another important opportunity is developing solutions to reduce competing uses for residues, such as alternative renewable and clean energy sources to replace the need to use residues as fuel. Creating an enabling environment is also important for the adoption of sustainable practices, which can include maintenance and repair services for new types of equipment and markets for new crops used as cover or in rotations.

The principal notion is that sustainable agriculture systems must meet the needs of farmers. Compatible management options or opportunities for innovation can only be identified with active farmer involvement and through adaptive research that seeks to create new forms of knowledge to address multifaceted challenges. It is also important to understand farmer decision making as well as farmer learning and experimentation. This requires participatory approaches to research and program design where farmers are co-creators of knowledge, rather than passive recipients of training and education. Farmers should not simply be expected to adopt packages of practices developed by external ‘experts’ but instead need to be highly active participants, even equal partners, in the co-creation of sustainable farming systems that meet their needs and reflect their realities. This suggested approach may contradict dominant narratives around ‘scaling’, ‘standardization’ or ‘replication’.

Govaerts et al. (2009) argue that multicomponent and knowledge-intensive technologies such as CA are unlikely to be successfully scaled out through traditional linear models of research and extension, but instead will require the development of innovation systems and decentralized learning hubs, comprising networks of farmer groups, machinery developers, extension practitioners, local businesses, and researchers, to adapt technologies to local conditions. Ongoing fashion-related Regenerative Agriculture pilots and initiatives should serve as the building blocks of these regional knowledge hubs, exchanging information and lessons learned with other hubs as well as international and national research centers to create a global understanding of how to best adapt sustainable agriculture approaches in cotton-based cropping systems in different agro-ecological zones and farmers' circumstances.

4.4 Applications for regenerative agriculture project design

Several pilot projects are already underway to develop 'regenerative organic' systems. There is no commonly agreed definition of regenerative agriculture, however many proponents view it as a natural evolution of organic farming, incorporating best soil conservation management practices. While the focus of this paper was Conservation Agriculture and not regenerative agriculture, the two are closely related. In fact, CA is often considered under the umbrella of regenerative agriculture. However, the application of this CA research to regenerative organic ambitions may be limited. As most CA publications assess the isolated effect of one or two practices, other variables were kept constant and highly controlled. Almost all the studies within the database used chemical fertilizers, pesticides, herbicides and/or defoliants, and many used Bt cotton or glyphosate-resistant cotton to address pest or weed pressures that are common to cotton.

Nevertheless, there are relevant learnings about the importance of adaptive management. Dealing with multiple and unpredictable threats is now the norm for farmers. Farming approaches that are too rigid may affect the ability of farmers to be responsive to the uncertain conditions in any given year. Unpredictable rainfall and the right water availability at each cotton growth stage was frequently mentioned as affecting the results of trials. Stevens et al. (1992) observed a mixed yield response with cotton yields increasing with tillage intensity in some years, and the reverse in others. Rainfall distribution during the growing season was noted as contributing to this variability and fruiting response to tillage and cover crops. Blaise (2015) reported a positive correlation between temperature, relative humidity, and evaporation rate with the number of bolls shed. In the reduced tillage trials of Mert et al. (2006), higher yield and more earliness occurred in years where abundant rainfall occurred after sowing but not in other years, arguing for adaptations in intra-row spacings. With living mulch trials, Bhaskar et al. (2018) experienced reduced cotton yields in a dry year, but in other years when soil moisture was not limiting the living mulch provided effective weed suppression and improved yields. However, above average rainfall can cause issues such as boll rot when coinciding with the boll formation stage (Blaise and Ravindran, 2003).

Increased weed pressures from switching to no-till was observed in several cases in the literature. While cover crops and narrow row spacing of cotton can address this over time, these are not always an option for farmers. Mavunganidze et al. (2014) discuss the reliance of Zimbabwe smallholder farmers on the hand hoe as the main method of weed control in conservation tillage systems. However, the farmers found it was not adequate to meet increased weed challenges. Constrained by capital and labor, herbicide usage may have increased their capacity to deal with weed pressures in the short-term. This stresses the importance of having a

more flexible approach, and the benefits of combining technologies if appropriate. This is a potential discrepancy between controlled experiments following scientific methodologies and brand or NGO-led regenerative agriculture initiatives and raises questions around how to best enable data sharing and promote more exchange between academia and industry.

4.5 Integrative sustainable agriculture approaches

As discussed in Section 1.3.4, the dominant approach in the sustainable cotton sector are standards- or practice-based. While CA is based on three core principles, it spans a wide range of types of conservation tillage, cover crop species, and crop diversification methods, many of which were captured in the CA literature reviewed. Furthermore, CA-based practices can be used in conjunction with soil amendments such as poultry litter, weed control tactics, or other agricultural technologies such as Integrated Pest Management (IPM), agroforestry or technologies that improve efficiency of water and nutrient use, depending on the local needs and availability of resources. An integrative sustainable farming approach should not focus on a single sustainable agriculture framework, but instead focus on the improvement of ecological and social processes and outcomes. Different combinations of cropping system, soil type, climate, management constraints, and history of management will require a tailoring of practices. The *DG Cotton and Soils Database* can be used as a starting base for sharing ideas and informing further stakeholder engagement.

The trend towards more outcomes-based strategies, as mentioned in Section 1.4.3., is a sign of movement in this direction. However, there is not yet consensus on which outcomes should be measured, which can vary according to which sustainable agriculture framework is under consideration. Jian et al. (2020) argue that there has been little effort to evaluate which indicators should be measured to consistently quantify resulting improvements in soil health

from CA practices. The benefits of soil health assessments that go beyond simply testing nutrient levels of soils has already been discussed. However, regular soil testing is costly and infrastructure for comprehensive assessments of soil health is not available at the scale or coverage necessary to facilitate this quickly enough in most countries. Improvements in satellite-based remote sensing and more advanced tools offer the ability to develop widespread and rapid assessments of soil health, pest pressures and crop stress. They also have applications for verifying the adoption of certain management practices, such as cover crops and certain types of conservation tillage. While direct measurement and observations will be required for ground-truthing, this can drastically lower the costs of monitoring and measuring progress towards sustainability goals.

CHAPTER 5

CONCLUSION

Alternative agricultural frameworks that prioritize restoring soil functionality are gathering momentum worldwide as a new paradigm for agriculture in the 21st century. CA-based practices are promoted as having the potential to reverse the soil degradation caused by decades of intensive farming practices by reducing soil erosion, building up organic matter, enhancing microbial activity and diversity, and increasing soil water-holding capacity.

The OECD and FAO project that cotton production will grow through both higher yields in some areas and land expansion in others. As production intensifies or land is converted to cotton cultivation, there is a danger that poor management practices will further degrade soil health with devastating consequences for crop production capacity, livelihoods, and ultimately the future of fashion supply chains. Despite the global nature of cotton production, this review found that cotton-related CA research has concentrated in the US and, to a much lesser extent, India. Further research is needed on the impact of changing management practices in cotton-based cropping systems in tropical climates, where the majority of cotton production is.

This paper and supplementary *DG Cotton and Soil Health Database* provides a starting point in understanding the existing evidence base of CA management practices in all the climates, soil types, and cropping systems that cotton is grown in today. This has highlighted both where CA-based practices have achieved positive soil health, yield, and fiber quality outcomes, and identified where there are knowledge gaps. This paper argues for more holistic measurements of soil health and tailored approaches with active farmer participation to ensure sustainable agricultural systems are developed based on local realities. This may be full adoption of CA, adopting components of CA, combining with other technologies, or not adopting CA at all

depending on socio-cultural context, farmer livelihood strategies, availability of equipment, institutional and political factors. Along with this adaptive and context-specific approach, a monitoring and verification framework that can account for multiple agricultural approaches and knowledge types is also needed to be able to measure progress towards critical sustainable outcomes and goals.

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APPENDICES

APPENDIX A

SUMMARY OF PUBLICATIONS IN *DG Cotton and Soils DB*

Location	Duration (years)	Practices	Depth (cm)	Indicators measured	References
Tennessee, USA	31	RT-CC	0-7.5	PCB	Mbuthia et al. (2015)
Tennessee, USA	4	RT-CC	0-30	P	Raper et al. (2000)
Georgia, USA	3	RT-CC	0-30	PC	Sainju et al. (2006)
Arkansas, USA	17	CC	0-90	PC	Keisling et al. (1994)
Alabama, USA	4	RT-CC	0-30	PC	Terra et al. (2005)
Alabama, USA	10	RT-CC-CR	0-20	PCB	Sainju et al. (2008)
Georgia, USA	3	RT-CC	0-120	PC	Sainju et al. (2006)
California, USA	4	CC-CR	0-15	PCB	Andrews et al. (2002)
Nagpur, India	18	CR	0-30	C	Blaise et al. (2006)
NSW, Australia	1	RT-CR	0-60	PCB	Hulugalle et al. (2004)
Texas, USA	20	RT	0-20	CB	Wright et al. (2005)
Texas, USA	5	RT-CR	0-90	PC	Wright et al. (2007)
Texas, USA	19	RT-CC	0-15	CB	Burke et al. (2019)
Tennessee, USA	29	RT-CC	0-10	PB	Nouri et al. (2021)
Texas, USA	5	CC-CR	0-5	B	Acosta-Martinez et al. (2017)
Mississippi, USA	5	RT-CC	0-15	PCB	Locke et al. (2012)
North Carolina, USA	1	RT	0-60	PCB	Franzluebbers et al. (2021)
Tennessee, USA	34	RT-CC	0-30	P	Nouri et al. (2019)
Texas, USA	16	RT	0-20	PC	Salinas-Garcia et al. (1997)
Alabama, USA	3	RT-CC			Nyakatawa et al. (2001)
Alabama, USA	1	RT-CC	0-45	PCB	Truman et al. (2003)
Nagpur, India	2	CC			Bhaskar et al. (2018)
Nagpur, India	5	RT	0-15	C	Blaise et al. (2003)
Nagpur, India	3	RT-CC	0-15	P	Blaise et al. (2011)

Location	Duration (years)	Practices	Depth (cm)	Indicators measured	References
New Delhi, India	3	RT			Das et al. (2014)
Punjab, India	2	RT	0-180	PC	Jalota et al. (2008)
New Delhi, India	4	RT-CC-CR	0-30	PC	Das et al. (2013)
Cerrado, Brazil	9	RT-CC-CR	0-40	C	Ferreira et al. (2020)
Itiquira, Brazil	2	RT-CC-CR	0-40	P	Anghinoni et al. (2019)
Costa Rica, Brazil	22	RT-CC	0-20	C	Rodrigues et al. (2021)
Sapezal, Brazil	14	RT-CC	0-20	C	Rodrigues et al. (2021)
NSW, Australia	3	RT-CR	0-30	PC	Constable et al. (1992)
NSW, Australia	8	RT-CR	0-60	PCB	Hulugalle et al. (1997)
Mississippi, USA	5	RT			Triplett et al. (1996)
NSW, Australia	5	RT-CR	0-60		Hulugalle et al. (2000)
Nagpur, India	3	RT			Blaise et al. (2006)
Sirsa Rajasthan state, India	3	RT			Nehra et al. (2005)
Texas, USA	6	RT		P	Bordovsky et al. (1994)
NSW, Australia	6	CC	0-30	C	Rochester et al. (2005)
Mbire District, Zimbabwe	3	RT-CC	0-20		Baudron et al. (2012)
Anyang City, China	3	CR			Zhang et al. (2007)
Southern Province, Zambia	4	RT-CC-CR	0-30	PCB	Thierfelder et al. (2010)
Queensland, Australia	12	RT-CR	0-60	PC	Hulugalle et al. (2007)
Alabama, USA	4	RT-CC	0-6	P	Schwab et al. (2002)
Mississippi, USA	2	RT			Pettigrew et al. (2001)
Punjab, Pakistan	4	RT	0-20	C	Ishaq et al. (2001)
Georgia, USA	4	RT		P	Endale et al. (2002)
Alabama, USA	2	RT-CC	0-90	PC	Nyakatawa et al. (2001)
Tennessee, USA	33	RT-CC			Nouri et al. (2020)
Mato Grosso, Brazil	2	RT-CR	0-20	PC	dos et al. (2020)
Texas, USA	5	RT-CC			DeLaune et al. (2020)
Sudan savanna, Benin	2	RT			Nafi et al. (2019)

Location	Duration (years)	Practices	Depth (cm)	Indicators measured	References
Sudan savanna, Burkina Faso	2	RT			Nafi et al. (2019)
Punjab, India	2	RT-CC			Choudhary. et al. (2016)
Tashkent, Uzbekistan	6	RT-CR		PC	Khaitov et al. (2014)
Cordoba, Spain	3	RT	0-30	PC	Cid et al. (2014)
North Cameroon	6	RT-CC			Naudin et al. (2013)
Texas, USA	3	RT-CC	0-8	C	Li et al. (2013)
Khorezm, Uzbekistan	3	RT			Devkota et al. (2013a)
Khorezm, Uzbekistan	2	RT	0-90	C	Devkota et al. (2013b)
Alabama, USA	3	CC			Price et al. (2012)
Alabama, USA	3	RT			Aulakh et al. (2011)
Arkansas, USA	2	CC			Norsworthy et al. (2011)
SE Anatolia, Turkey	3	RT	0-30	PC	Gursoy et al. (2011)
Winde, Cameroon	3	RT-CC		B	Brevault et al. (2007)
Georgia (southern), USA	3	RT-CC	0-15	CB	Sainju et al. (2007)
Georgia, USA	2	CC		B	Schomberg et al. (2004)
Punjab, India	2	RT	0-15	PC	Choudhary et al. (2015)
Cordoba, Spain	3	RT	0-30	P	Boulal et al. (2012)
Srivilliputtur, India	2	RT			Veeraputhiran et al. (2020)
Louisiana, USA	6	RT-CC			Boquet et al. (2004)
Mississippi, USA	3	RT-CC			Stevens et al. (1992)
South Carolina, USA	3	RT			Roach et al. (1981)
Oklahoma, USA	5	RT			Porterfield et al. (1974)
Nagpur, India	5	CC		B	Blaise et al. (2021)
South Carolina, USA	2	RT-CC		P	Bauer et al. (1996)
Georgia, USA	2	RT			Buntin et al. (2002)
Dera Ismail Khan, Pakistan	2	RT		PC	Usman et al. (2014)
Dera Ismail Khan, Pakistan	2	RT	0-60		Usman et al. (2013)
Koruklu, Turkey	2	RT			Ozpinar et al. (2004)

Location	Duration (years)	Practices	Depth (cm)	Indicators measured	References
Mississippi, USA	5	RT		P	Smith et al. (1995)
, Sudan	2	RT		P	Ahmed et al. (1993)
NSW, Australia	7	RT	0-60	PC	Wild et al. (1992)
Tennessee, USA	12	RT-CC-CR	0-15	C	Ashworth et al. (2016)
California, USA	3	RT		P	Carter et al. (1965)
Assiut, Egypt	1	RT		P	Ismail et al. (2006)
NSW, Australia	3	RT		P	Hulme et al. (1996)
Kafr El-Sheikh, Egypt	1	RT	0-60	P	El-Khateeb et al. (2009)
Fars province, Iran	2	RT	0-60	P	Roozbeh et al. (2021)
Arkansas, USA	2	CC			Norsworthy et al. (2010)
Akola, India	2	RT			Karishma et al. (2019)
Nagpur, India	10	RT			Blaise et al. (2015)
Multan, Pakistan	1	RT-CC		PCB	Saleem et al. (2022)
Dera Ismail Khan, Pakistan	5	RT	0-30	PC	Khan et al. (2021)
Henan Province, China	2	CC	0-100	C	Zhang et al. (2021)
Yellow River basin, China	3	CC	0-100	C	Wang et al. (2021)
Hebei, China	7	CR	0-20	C	Yang et al. (2014)
Yellow River basin, China	2	CC	0-20	C	Sun et al. (2022)
Texas, USA	4	RT-CC		P	Baumhardt et al. (1999)
Southern Province, Zambia	14	RT	0-30	PC	Mhlanga et al. (2021)
, India	10	RT	0-30	C	Yadav et al. (2021)
Mississippi, USA	7	RT	0-7.6	PC	Locke et al. (2015)
Texas, USA	2	RT	0-15	C	McDonald et al. (2019)
Mississippi, USA	5	RT-CR			Wesley et al. (2001)
Florida, USA	10	CC-CR	0-60	PC	Gamble et al. (2019)
South Carolina, USA	37	RT-CC	0-15	C	Novak et al. (2020)
Tennessee, USA	17	RT-CC-CR	0-30	PC	Bansal et al. (2021)
Georgia, USA	13	CR			Sorensen et al. (2020)

Location	Duration (years)	Practices	Depth (cm)	Indicators measured	References
Mississippi, USA	3	RT-CC	0-5	CB	Zablotowicz et al. (2011)
Mato Grosso, Brazil	9	RT	0-100	PC	Souza et al. (2018)
Alabama, USA	6	RT-CC	0-15	PC	Balkcom et al. (2013)
Cordoba, Spain	2	RT	0-20	CB	Panettieri et al. (2013)
Alabama, USA	3	RT-CC		PB	Brown et al. (1985)
Alabama, USA	5	RT-CC			Reddy et al. (2004)
Alabama, USA	100	CC-CR		C	Mitchell et al. (1998)
Mississippi, USA	3	RT-CC			Parvin et al. (2004)
Mississippi, USA	6	RT		C	Reddy et al. (2017)
Tennessee, USA	12	CC-CR	0-15	CB	Ashworth et al. (2017)
Texas, USA	23	RT-CC	0-60	PC	Burke et al. (2022)
Dera Ismail Khan, Pakistan	2	RT	0-30	PC	Khan et al. (2014)
Texas, USA	17	RT-CC	0-90	PC	DeLaune et al. (2019)
Texas, USA	17	RT-CC	0-140	P	Burke et al. (2021)
Texas, USA	17	RT-CC	0-60	C	Lewis et al. (2018)
Texas, USA	3	RT	0-230	P	Baumhardt et al. (2013)
Alabama, USA	2	CC	0-30	PC	Johnson et al. (2021)
Georgia, USA	4	RT-CC			Schomberg et al. (2006)
NSW, Australia	6	RT-CR	0-120	P	Tennakoon et al. (2006)
Xinjiang, China	2	RT	0-120	PC	Bai et al. (2021)
Dera Ismail Khan, Pakistan	2	RT			Khan et al. (2014)
SE Anatolia, Turkey	1	RT			Gursoy et al. (2012)
Hatay province, Turkey	1	RT			Mert et al. (2006)
Aegean region, Turkey	2	RT-CC			Unay et al. (2005)
Aegean region, Turkey	2	RT			Yalcin et al. (2005)
Alabama, USA	21	RT-CC-CR	0-30	CB	Motta et al. (2007)
Bhopal, India	3	RT	0-45	PCB	Somasundaram et al. (2019)

APPENDIX B

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