



HAL
open science

Major Crops and Climate Change: The Cases of Rice, Sorghum, Sugarcane and Cotton

Alexia Prades, Patricio Mendez del Villar, Didier Tharreau, Edward Gérardiaux, Raphaëlle Ducrot, Aude Ripoche, David Pot, Mohamed Lamine Tékété, Cyril Diatta, Laurent Laplaze, et al.

► To cite this version:

Alexia Prades, Patricio Mendez del Villar, Didier Tharreau, Edward Gérardiaux, Raphaëlle Ducrot, et al.. Major Crops and Climate Change: The Cases of Rice, Sorghum, Sugarcane and Cotton. Vincent Blanford; Marie Hrabanski; Julien Demenois. Climate Impacts and Challenges in Agriculture, Forests and Food Systems. Perspectives on the Global South, Springer; Editions Quae; Cirad, pp.205-227, 2026, 978-3-032-04331-3. <10.1007/978-3-032-04331-3_13>. <hal-05576772>

HAL Id: hal-05576772

<https://hal.science/hal-05576772v1>

Submitted on 2 Apr 2026

HAL is a multi-disciplinary open access archive for the deposit and dissemination of scientific research documents, whether they are published or not. The documents may come from teaching and research institutions in France or abroad, or from public or private research centers.

L'archive ouverte pluridisciplinaire HAL, est destinée au dépôt et à la diffusion de documents scientifiques de niveau recherche, publiés ou non, émanant des établissements d'enseignement et de recherche français ou étrangers, des laboratoires publics ou privés.



Distributed under a Creative Commons CC BY-NC-ND 4.0 - Attribution - Non-commercial use - No Derivative Works - International License

Vincent Blanford · Marie Hrabanski
Julien Demenois *Editors*

Climate Impacts and Challenges in Agriculture, Forests and Food Systems

Perspectives on the Global South

éditions
Quæ

Éditions Cirad, Ifremer, INRAE
www.quae.com

 **cirad**
AGRICULTURAL RESEARCH
FOR DEVELOPMENT

OPEN ACCESS

 **Springer**

Climate Impacts and Challenges in Agriculture, Forests and Food Systems

Vincent Blanford • Marie Hrabanski
Julien Demenois
Editors

Climate Impacts and Challenges in Agriculture, Forests and Food Systems

Perspectives on the Global South

Second Edition

 Springer

Editors

Vincent Blanfort
Cirad joint research unit Selmet “Tropical
and Mediterranean Animal Production
Systems”, Montpellier Univ, Inrae
Institut Agro
Montpellier, France

Marie Hrabanski
Cirad UMR Actors Resources
Territories & Development (ART-Dev)
Montpellier, France

Julien Demenois
CIRAD UPR Agroecology and sustainable
intensification of annual crops (Aïda)
Montpellier, France



ISBN 978-3-032-04330-6 ISBN 978-3-032-04331-3 (eBook)
<https://doi.org/10.1007/978-3-032-04331-3>

Translation from the French language edition: “L’agriculture et les systèmes alimentaires du monde face au changement climatique” by Vincent Blanfort et al., © Éditions Quæ 2025. Published by Éditions Quæ. All Rights Reserved.

Jointly published with Éditions Quæ, Versailles, France

The original submitted manuscript has been translated into English. The translation was done using artificial intelligence. A subsequent revision was performed by the author(s) to further refine the work and to ensure that the translation is appropriate concerning content and scientific correctness. It may, however, read stylistically different from a conventional translation.

This book is an open access publication.

© Editions Quæ 2016, 2026

Open Access This book is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this book or parts of it.

The images or other third party material in this book are included in the book’s Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the book’s Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

The use of general descriptive names, registered names, trademarks, service marks, etc. in this publication does not imply, even in the absence of a specific statement, that such names are exempt from the relevant protective laws and regulations and therefore free for general use.

The publisher, the authors and the editors are safe to assume that the advice and information in this book are believed to be true and accurate at the date of publication. Neither the publisher nor the authors or the editors give a warranty, expressed or implied, with respect to the material contained herein or for any errors or omissions that may have been made. The publisher remains neutral with regard to jurisdictional claims in published maps and institutional affiliations.

This Springer imprint is published by the registered company Springer Nature Switzerland AG
The registered company address is: Gewerbestrasse 11, 6330 Cham, Switzerland

If disposing of this product, please recycle the paper.

Chapter 13

Major Crops and Climate Change: The Cases of Rice, Sorghum, Sugarcane and Cotton



Alexia Prades, Patricio Mendez del Villar, Didier Tharreau, Edward Gérardaux, Raphaëlle Ducrot, Aude Ripoche, David Pot, Mohamed Lamine Tékété, Cyril Diatta, Laurent Laplaze, Boris Parent, Isabelle Basile-Doelsch, Christine Granier, Myriam Adam, Julie Dusserre, Michel Vaksmann, Mathias Christina, Christophe Poser, Bruno Bachelier, and Romain Loison

Abstract This chapter discusses how climate change poses major challenges for tropical crops like rice, sorghum, sugarcane, and cotton, which are mostly grown on small family farms. While large-scale farming is a major contributor to greenhouse gas emissions, these smallholder systems also have an environmental impact. Crops like flooded rice and burned sugarcane fields emit GHGs, and all four crops are vulnerable to climate change. Cotton, though less directly affected, faces risks due to water dependence and pest pressure. The chapter outlines production systems, climate impacts, and proposes adaptation and mitigation strategies.

A. Prades
Cirad, DGD-RS, Montpellier, France
e-mail: alexia.prades@cirad.fr

P. M. del Villar (✉)
Cirad, UMR TETIS, Univ Montpellier, AgroParisTech, Cirad, CNRS, INRAE,
Montpellier, France
e-mail: patricio.mendez@cirad.fr

D. Tharreau
Cirad, UMR PHIM, Montpellier, France

E. Gérardaux · J. Dusserre · M. Christina · C. Poser · B. Bachelier · R. Loison
Cirad, UPR Agroecology and Sustainable Intensification of Annual Crops (Aïda),
Montpellier, France

Aïda, Univ. Montpellier, Cirad, Montpellier, France

R. Ducrot
Cirad, UMR G-EAU, Royal University of Agriculture, Phnom Penh, Cambodia

A. Ripoche
Cirad, UR GECCO, Station de La Bretagne, Saint-Denis, La Réunion, France

13.1 Introduction: Tropical Crops Facing Climate Change, Significant Challenges for Predominantly Family Farming

Alexia Prades

Cirad, DGD-RS, Montpellier, France

In certain parts of the world, it is now accepted that large-scale farming significantly contributes to climate change, as they have been conducted since the 1945–1950 period, through massive intensification processes, consuming chemical inputs, energy from fossil resources, and generating greenhouse gases (GHGs). In all OECD countries, total GHG emissions from agriculture have increased on average by 3.8% between 2005 and 2021.

The term *large-scale farming*, used in this chapter and applied to developing countries in tropical and subtropical areas, might appear inappropriate, as the cereals (rice, sorghum) or commercial crops (sugarcane, cotton) presented here are mostly extensively grown on small family farms. They contribute either directly as

D. Pot

Cirad, UMR AGAP Institute, Montpellier, France

UMR AGAP Institute, Univ Montpellier, Cirad, INRAE, Institut Agro, Montpellier, France

M. L. Tékété

Rural Economy Institute, Bamako, Mali

C. Diatta

Regional Study Centre for Drought Adaptation Improvement, Senegalese Institute of Agricultural Research, Thiès, Senegal

L. Laplaze

UMR DIADE, University of Montpellier, IRD (Research Institute for Development), Montpellier, France

B. Parent

UMR LEPSE, University of Montpellier, INRAE, Institut Agro, Montpellier, France

I. Basile-Doelsch

Aix-Marseille University, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France

C. Granier

INRAE, UMR AGAP Institute, Montpellier, France

M. Adam

Cirad, UMR AGAP Institute, Montpellier, France

UMR AGAP Institute, Univ Montpellier, Cirad, INRAE, Institut Agro, Montpellier, France

Faculty of Agriculture and Food Processing, National University of Battambang, Battambang, Cambodia

M. Vaksman

Cirad, UMR AGAP Institute, Montpellier, France

UMR AGAP Institute, Univ Montpellier, Cirad, INRAE, Agro Institute, Montpellier, France

food or indirectly as a source of income to the food security of millions of families and take part to the food and energy sovereignty of these countries (Sourisseau 2014). Indeed, rice, sorghum, sugarcane, and cotton crops also contribute, to varying degrees, to climate change. But while it has been proven that flooded rice fields emit methane and that the practice of burning for sugarcane produces GHGs, it has also been proven that these crops will be greatly affected by climate change. Given the existing knowledge, this seems a little less true for cotton species. However, the dependence of this crop on water resources and its sensitivity to the pressure of pests are factors those farmers will have to take into account.

This chapter presents key facts on the production of four major crops cultivated in tropical areas: rice, sorghum, sugarcane, and cotton. For each of them, it includes a description of the production systems and their international context. It describes the impacts of climate change on the production and ends with proposals of solutions for adaptation and mitigation.

13.2 Towards Rice Farming Adapted to Global Changes

Patricio Mendez del Villar, Didier Tharreau, Edward Gérardaux,
Raphaëlle Ducrot, and Aude Ripoché

Cirad, UMR TETIS, Univ Montpellier, AgroParisTech, Cirad, CNRS, INRAE,
Montpellier, France

Cirad, UMR PHIM, Montpellier, France

Cirad, UPR Agroecology and Sustainable Intensification of Annual Crops
(Aïda), Montpellier, France

Aïda, Univ. Montpellier, Cirad, Montpellier, France

Cirad, UMR G-EAU, Royal University of Agriculture, Phnom Penh, Cambodia

Cirad, UMR Aïda, Station de La Bretagne, Saint-Denis, La Réunion, France

13.2.1 *Rice Feeds Half of Humanity*

Rice is the staple food for more than half of the world's population, particularly the poorest. In many Southern countries, food security and social and political stability depend on the availability of rice at “affordable” prices. Rice is also a source of household income in many countries. It is also an essential commodity for emergency aid when it comes to meeting the needs of populations after extreme weather events, the frequency and amplitude of which are increasing.

The more than a thousand-year-old exploitation of many rice plains continuously (without crop rotation and sometimes in double or triple annual culture) testifies to the resilience of aquatic rice ecosystems that provide more than three-quarters of the world's production. In many regions of the world, including Europe and France, rice farming also plays an important role in sustainable development and in the conservation of biodiversity in delta areas. Rice is also grown in more fragile mangrove and non-flooded ecosystems (strict rainfed rice farming), particularly in Africa and Latin America.

13.2.2 Diversified Rice Systems

One of the characteristics of the rice sector is probably the great diversity of existing agro-socio-economic situations. This diversity includes the integration of rice farming into complex agricultural systems (for example, rice-fish farming), including livestock, and interaction with other sectors (for example, market gardening). While keeping this diversity in mind, it is nevertheless possible to identify quite distinct characteristics of the sector: three main agrosystems (irrigated rice farming, lowland and strict rainfed), subsistence farming *vs* Marketed production, including for export, input-intensive *vs* labour-intensive, small producers *vs* large producers. Certain combinations of these characteristics correspond to very representative agro-socio-economic situations on a global scale: small but intensive farming producers in Asia, small producers with low input use in Sub-Saharan Africa, large intensive farming producers in South America, particularly in southern Brazil, in Uruguay and Argentina. These situations can be likened to different value chains, each facing different challenges and defining a different initial context to be taken into account when implementing changes.

13.2.3 A Global Rice Market Facing Global Shocks

By 2023, according to the FAO (2025), global paddy rice production had reached 805 Mt. (or 535 Mt. in milled rice basis), of which nearly 90% are produced and consumed in Asia. The Asian continent is also the main surplus hub and rice supplier for the rest of the world, particularly Sub-Saharan Africa, the main rice deficit area and the leading import hub with a third of global imports. Despite a high production potential in arable lands, Sub-Saharan Africa thus has to import between 30% and 50% of the rice consumed. This external dependence strongly exposes it to the instability of international markets and increases food insecurity (availability and access), especially in urban areas.

The 2008 crisis, illustrated by the surge in global prices, was a significant shock, especially for the most impoverished populations. To respond to this crisis, African governments, with their international partners, have implemented new policies to support local sectors with the aim of achieving rice self-sufficiency. However, support programmes are not achieving the expected goals of significantly reducing rice dependence on the international market. Crises of all kinds, like the Covid-19 pandemic or the war in Ukraine, combined with climate change, underline the need to develop more resilient rice systems. However, on certain national markets in the South, local production sectors are facing the globalisation of trade and are subject to the competition of import sectors. The low added value of sectors promoting quality for export (organic or *sustainable rice*) is a contextual element to be taken into account.

Global rice sectors must face multiple challenges of different kinds (biophysical and environmental, technical, socio-economic and political), which add additional constraints to climate change management. The first of these is to generate value, distribute it equitably among actors, and improve the living standards of 400 million poor rice farmers to reduce inequalities, without prejudice to the 500 million consumers living below the poverty line for the majority of them.

13.2.4 Meeting the Needs of Consumers

Another significant challenge is to respond to the diversification of demands in terms of organoleptic and industrial quality of rice, and to increased requirements for nutritional and health quality. Quality is a challenge throughout the value chain, from the production to the consumption of rice. This involves not only addressing the technological issue (research on plant functioning, organoleptic qualities, etc.), but also leveraging this quality to better value rice commercially, which simultaneously requires organisational innovations.

13.2.5 Rice Systems, Living Spaces

Beyond considerations related to the marketing of rice, irrigated rice-growing areas are territories in which populations are settled and live. The permanent presence of water gives these areas a great specificity with, in particular, consequences on human health, issues on water uses, a particular vulnerability to climate change. Irrigated rice farming is also a significant source of GHGs (methane, nitrous oxide) in agriculture and therefore at the heart of issues related to climate change (IPCC 2021a; Sinha et al. 2020).

13.2.6 Meeting Future Food Security in the Face of Global Changes

On a global scale, the challenges to be met in terms of production can be summarised as follows: for each additional billion people in the world population, an additional 100 Mt. of paddy rice (13% of total production in 2024) per year would need to be produced (Trébuil and Hossain 2004); and this with less land, less water and less labour, with more environmentally friendly production systems, more resilient to climate change and emitting less GHGs. By 2025, 10–15% of irrigated rice fields will be subject, to varying degrees, to a water constraint resulting from increased urban and industrial demands and the effects of climate change (Tuong and Bouman 2003).

Rice farming must therefore, more than any other crop, face the instability of the climate and its consequences: the increase in daytime and nighttime temperatures can harm flowering and therefore production; the increase in CO₂ atmospheric increase in biomass and if nutrient availability cannot meet the increased demand, the biomass gain will not translate into grain yield gains. This situation can even impair quality. Drought, soil salinity and flooding are increasingly frequent abiotic constraints that reduce yields (Lafarge et al. 2015; Ahmadi et al. 2015). Climate change can also promote the emergence or re-emergence of rice diseases that strongly affect yields and quality.

In a context of climate change, whose impacts are intensifying, water, necessary for the majority of rice systems, is becoming scarce and the multiplication of its uses reinforces competition between users in the same territory. The rice sector will thus have to manage the high consumption of a water resource under stress in irrigated systems in Asia, Africa and Latin America. It will be necessary to produce with less water and co-develop (up to sustainable appropriation) organisational and institutional innovations for better conflict management around this precious resource. Better water management can also contribute to promoting efficient systems emitting less GHGs. Rice cultivation is indeed responsible for a significant part of anthropogenic GHG emissions (22% of global agricultural methane emissions) (IPCC 2021a, b).

13.2.7 The Agroecological Transition in Rice Cultivation, a Technical Challenge

Global rice cultivation will also have to face technical challenges related to climate change. How to stabilise or increase production while limiting negative impacts on humans and the environment? The demand for rice will continue to increase due to the growth of the world population by an additional two billion by 2050, including one billion in Africa.¹ In input-intensive systems, particularly in Asia, the objective

¹ UN, 2024. Population. <https://www.un.org/en/global-issues/population>

will be to produce more by reducing the use of chemical inputs (fertilizers, pesticides) and accompanying the potential reduction of labour (mechanization). Reducing the use of certain synthetic inputs improves the carbon balance, but it also reduces the dependence of rice farmers on often imported products, not always available or accessible, and dependent on global geopolitical stability. Finally, reducing inputs contributes to reducing production costs given the increase in prices. In Africa, the context is quite different as the quantities of chemical fertilizers are relatively reduced (between 100 and 200 kg/ha), this being largely due to financial constraint and their reduced availability; a situation that tends to worsen with the quadrupling of fertilizer prices between 2020 and 2022, due to the pandemic, and with new increases since the war in Ukraine in 2022 and its repercussions on international trade.

Certain rice agrosystems (deltas, protected areas, rainfed rice cultivation) are particularly fragile and must receive special attention. Agroecological solutions are a way to protect them. Increasing plant diversity in rice systems is necessary to limit soil fertility loss and to increase resilience to climate change, but it remains a significant technical challenge in irrigated or flooded rice cultivation.

13.3 Sorghum and Climate Change: Balancing Adaptation Needs with Mitigation Potential

David Pot, Mohamed Lamine Tékété, Cyril Diatta, Laurent Laplaze, Boris Parent, Isabelle Basile-Doelsch, Christine Granier, Myriam Adam, Julie Dusserre, and Michel Vaksman

Cirad, UMR AGAP Institute, Montpellier, France

UMR AGAP Institute, Univ Montpellier, Cirad, INRAE, Institut Agro, Montpellier, France

Rural Economy Institute, Bamako, Mali

Regional Study Centre for Drought Adaptation Improvement, Senegalese Institute of Agricultural Research, Thiès, Senegal

UMR DIADE, University of Montpellier, IRD (Research Institute for Development), Montpellier, France

UMR LEPSE, University of Montpellier, INRAE, Institut Agro, Montpellier, France

Aix-Marseille University, CNRS, IRD, INRAE, CEREGE, Aix-en-Provence, France

INRAE, UMR AGAP Institute, Montpellier, France

Faculty of Agriculture and Food Processing, National University of Battambang, Battambang, Cambodia

Cirad, UPR Agroecology and Sustainable Intensification of Annual Crops (Aïda), Montpellier, France

Aïda, Univ. Montpellier, Cirad, Montpellier, France

UMR AGAP Institute, Univ Montpellier, Cirad, INRAE, Agro Institute, Montpellier, France

Sorghum, a species native to northeastern Africa, has a dual identity. It is, on one hand, a cornerstone of food security in semi-arid regions around the world; on the other, it serves as a driver of agroecological transition in the production systems of Northern countries. In both contexts, sorghum must adapt to the challenges posed by climate change, while also contributing to its mitigation.

13.3.1 Sorghum: Ensuring Food Security and Driving the Agroecological Transition

Sorghum ranks as the fifth most produced cereal worldwide and serves as the staple food for over 500 million people living in semi-arid regions. It is extensively cultivated—covering more than 5000 hectares per country—in 72 countries, occupying a total global area of 40.2 Mha, with an average annual production of 59.1 Mt. (between 2018 and 2022).

The largest sorghum cultivation areas are found in sub-Saharan Africa—particularly in Sudan and South Sudan (7.6 Mha), Nigeria (5.69 Mha), and Niger (3.72 Mha)—as well as in India (4.42 Mha) and in the United States (2.09 Mha). In Europe, on average 277,000 ha of sorghum were cultivated annually between 2018 and 2022. On the same period, the five largest sorghum-producing countries were the United States (8.71 Mt./year), Nigeria (6.71 Mt./year), Ethiopia (4.79 Mt./year), Mexico (4.54 Mt./year), and India (4.40 Mt./year).

In West Africa, sorghum yields have changed little between 1998–2002 and 2018–2022, with only a modest increase of 6.4%. As a result, production growth in the region has largely been driven by the expansion of cultivated areas.

In Africa, human consumption—which encompasses a wide variety of food products—accounts for nearly three-quarters of total sorghum use. In contrast, in Northern and emerging countries, sorghum is primarily used as animal feed. Additionally, it is emerging as a key crop for bioenergy production (Thomas et al. 2021) and shows promising potential for the development of biomaterials.

The development of sorghum-based value chains is supported by the crop's distinctive biological characteristics. As a C4 photosynthetic species, sorghum exhibits efficient carbon assimilation under high-temperature conditions. Its strong tolerance to abiotic stresses—particularly water scarcity and low soil fertility—has been well documented (Schlegel et al. 2018), contributing to its relatively low environmental footprint. Finally, although it can be affected by various pests and diseases, sorghum remains a robust species with a relatively low sensitivity to biotic stress, thereby requiring minimal plant protection treatments.

13.3.2 How Climate Change Is Shaping Sorghum Production

Climate change is already impacting West Africa. Between 2000 and 2009, a 1 °C increase compared to pre-industrial levels resulted in sorghum yield reductions ranging from 5% to 15% (Sultan et al. 2019).

Future projections indicate varying degrees of yield reductions. In West Africa, climate scenarios of +1.5 °C and + 2 °C predict yield declines (excluding Niger) of approximately 2% and 5%, respectively, regardless of fertilization levels (Faye et al. 2018). More recent projections from 2020, covering the five main sorghum-producing countries in West Africa, estimate losses between 15% and 28% (Defrance et al. 2020). Notably, Niger appears to benefit from a favorable impact of climate change.

Yield reductions are therefore to be expected, but these data alone cannot predict whether the needs of the populations will be met. Considering the evolving needs of the populations in West Africa (+300% based on demographic changes) there is a substantial anticipated gap between demand and future sorghum production capacity (Defrance et al. 2020).

Changing environmental conditions are also expected to impact sorghum quality. Under water deficit conditions, increases in grain hardness and protein content have been observed, alongside a decrease in protein digestibility and alterations in micronutrient balance (Impa et al. 2019). In contrast, heat stress leads to reductions in protein content and digestibility, coupled with an increase in grain hardness. Both stresses are associated with an overall decline in micronutrient levels (Impa et al. 2019).

The quality of sorghum biomass, which is crucial for both animal feed and bio-energy production, will also be impacted by environmental stress. Water deficit has been shown to increase soluble sugar content while reducing lignin and cellulose levels in stems (Luquet et al. 2019).

However, it is important to emphasize that, for both grain and biomass, the impacts on the final products consumed or utilized have yet to be thoroughly analyzed.

13.3.3 Sorghum: A Contributor to Climate Change Mitigation

The potential of crops to mitigate climate change primarily relies on two mechanisms: their capacity to sequester atmospheric carbon in the soil and their ability to reduce greenhouse gas emissions, including CO₂, CH₄, and N₂O.

Regarding soil carbon sequestration, sorghum benefits from a deep root system. A recent comprehensive study of biomass contributing to carbon storage—particularly through the incorporation of crop residues into the soil—across cereals and legumes in Africa and Asia was provided by Kuyah et al. (2023). This study reveals that sorghum ranks among the cereals with the highest potential for carbon storage in both above-ground biomass and root systems, emphasizing the significant role of carbon released through rhizodeposition.

The most comprehensive study to date—considering both geographical scope and duration—estimates CO₂ emissions at 250 g CO₂ per kilogram of sorghum grain produced.² Although these figures should be interpreted cautiously, they compare favorably to maize grain emissions in the same region, which are estimated at 390 g CO₂/kg (Adom et al. 2012). In Sub-Saharan Africa, the use of sorghum straw to supplement the poor-quality forage available at the end of the dry season has been shown to reduce enteric methane emissions from ruminants (Fulani zebu) by 21% (Gbenou et al. 2024).

Regarding N₂O emissions, sorghum's root exudates have been shown to inhibit soil nitrification, which may lead to lower emissions compared to other major crops (Subbarao et al. 2013).

13.3.4 Sorghum in a Changing Climate: Strategies for Adaptation and Climate Mitigation

Despite sorghum's inherent resilience, its cultivation systems must evolve to meet the future demands of producers and consumers. Notably, farmers are already adapting to climate change by drawing on traditional knowledge—adjusting sowing dates and varieties, relocating crops to more favorable environments, and adopting water-saving techniques (Amadou et al. 2022) as well as crop diversification strategies (Traore et al. 2023). This highlights the critical importance of fostering close collaboration between farmers and researchers to develop effective solutions that mitigate the anticipated adverse impacts of climate change.

Optimizing cropping systems that integrate sorghum-legume associations (such as cowpea and others; see Chap. 21) will be a crucial strategy for adaptation. Access to fertilizers will also play a key role in maintaining or even increasing yields, although it may increase the system's vulnerability to climate change (Adam et al. 2020). The development of improved varieties is equally essential. Beyond adjusting phenology and selecting for the stay-green trait—already key targets of breeding programs (see Chap. 21)—additional traits must be considered. Although sorghum is generally regarded as drought-tolerant, significant variability exists within its genetic diversity, and the underlying physiological and genetic mechanisms remain largely unexplored. It is therefore critical to deepen our understanding of water use efficiency by examining the plant's hydraulic traits, including the aerial apparatus (e.g., transpiration efficiency, xylem cavitation) and the root system (anatomy, architecture, and rhizodeposition). A detailed analysis of root anatomy, exudate production, and the plant's ability to recruit beneficial microbiome partners will also enhance soil carbon sequestration potential. Finally, the development of resilient varieties and sustainable cropping systems must address the combined and recurrent stresses—such as drought and heat—that plants will increasingly face in the future.

²SGS North America, 2015. The-Carbon-Footprint-of-Sorghum.pdf.

13.3.5 Evolution of Sorghum Production Systems: Towards a Multi-Species Approach Embracing Diverse Production Contexts

The evolution of sorghum-based production systems will need to acknowledge the roles and benefits of associated crops, inevitably leading to changes in both cultivation practices and the traits targeted in new varieties. Consumer needs must be systematically and more thoroughly integrated to guide the desired development of cropping systems and variety selection. Identifying relevant ideotypes—optimal trait combinations—will undoubtedly benefit from advances in comparative and translational biology. Rather than framing sorghum and maize as simple opposites—with sorghum traditionally viewed as more drought-tolerant, a notion now being challenged (Rotundo et al. 2024)—synergies between research on these two crops should be fostered for the advantage of both producers and consumers. Finally, it is essential to recognize that adapting cropping systems to future conditions will depend not only on agronomic factors such as yield and product quality, but also on socio-economic considerations, including labor availability and the potential for intensification (e.g., input quality and availability, biomass flow management).

13.4 Sugarcane in the Face of Climate Change

Mathias Christina and Christophe Poser

Cirad, UPR Agroecology and Sustainable Intensification of Annual Crops (Aïda), Montpellier, France

Aïda, Univ. Montpellier, Cirad, Montpellier, France

13.4.1 Impacts and Challenges Related to Climate Change for Sugarcane Cultivation

Sugarcane cultivation is an economic pillar for many tropical and subtropical countries, providing not only sugar for human consumption, but also biofuels, animal feed and bedding, and industrial by-products. Sugarcane is currently grown on about 26 million hectares of agricultural land worldwide, employing millions of people in the cultivation, transport, processing and distribution sectors. The largest global producers are located in Brazil, Southeast Asia (India, China, Thailand), but sugarcane is also present in all tropical and subtropical areas (United States, South and West Africa, Australia). Faced with increasing demand, cultivation areas are expanding.

Like other major crops such as corn or wheat, sugarcane cultivation significantly contributes to GHG emissions (Tongwane et al. 2016). The cultivation process represents the majority of emissions compared to the industrial transformation process (Macedo et al. 2008), due to mechanisation, the use of chemical inputs or the practice of burning, which is still common in some countries, although its cessation is widely promoted to limit GHGs. For example, a study, conducted in Brazil between 2005 and 2006, showed that the transport of sugarcane after harvesting accounted for only 7% of GHG emissions, compared to 11% for the production of fertilisers and 19% resulting from the practice of burning (Macedo et al. 2008).

Climate change also poses a serious threat to this industry, but the expected consequences vary greatly depending on the areas concerned (Linnenluecke et al. 2018). The challenges are numerous: variations in precipitation patterns, rising temperatures, rising sea levels in coastal areas and the increased frequency of extreme weather events such as cyclones and floods (Warren et al. 2024).

Studies have shown contrasting projections depending on the climate zones, due to the combination of favourable conditions for C4 crops³ (increase in temperature and CO₂) and unfavourable precipitation patterns (Fig. 13.1). Indeed, sugarcane requires specific climate conditions to grow optimally. It thrives in regions where rainfall is abundant, ideally over 1500 mm per year, and where average daily temperatures are between 22 °C and 30 °C.⁴ Well-drained and fertile soils are also essential for high yields. However, the increase in average temperatures and the increased variability of precipitation make crop management more difficult and compromise yield stability.

The impacts of climate change on sugarcane are multiple and varied. Changes in precipitation patterns can lead to more frequent and severe drought periods (Carvalho et al. 2015), affecting the growth of sugarcane which requires regular water inputs to maximise yields (Jones et al. 2015). Good irrigation management could indeed increase yields in many regions (Linnenluecke et al. 2018). However, the decrease in precipitation and the increase in evapotranspiration due to higher temperatures reduce the availability of fresh water, exacerbating competition for this resource between agriculture, domestic and industrial uses and even more in the context of a demand for improved water quality.

The increase in temperatures also poses a significant challenge. The maturation of the sugarcane (accumulation of sugar in the stems) is disrupted by excessive heat, particularly by the increase in night-time minimums. In addition, higher temperatures and humidity promote the proliferation of pests and diseases, such as brown rust of sugarcane or weeds, which can harm production (Goebel and Sallam 2011). However, the increase in temperatures is seen as more beneficial for sugarcane cultivation in many regions, provided there is satisfactory water availability.

³C4 crop: a crop whose photosynthesis is of the C4 type, meaning that the first carbohydrate formed has four carbon atoms. C4 plants are characterised by a higher photosynthetic yield and better water use than C3 plants.

⁴<https://www.fao.org/land-water/databases-and-software/crop-information/sugarcane/en/>

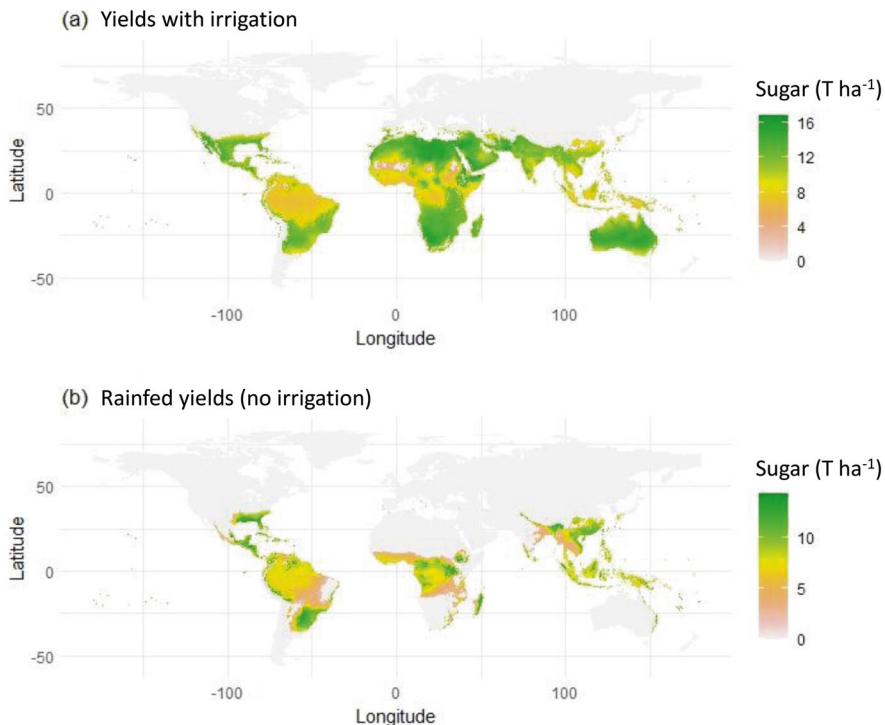


Fig. 13.1 Example of a gradient of potential sugarcane yields in the context of climate change: period 2041–2070. (Source: data from gaez-services.fao.org). Sugar yield (t/ha) under irrigated (a) or rainfed (b) conditions, GFDL-ESM2M climate model, RCP4.5 scenario. The maps show a colour gradient from brown for low sugar yields to green for high sugar yields worldwide. Two situations are represented, with irrigated yields at the top and non-irrigated yields at the bottom. They illustrate the diversity of situations that will be encountered by the main sugarcane producing countries in the future between 2040 and 2070

The rise in sea level could also exert increasing pressure on sugarcane production areas (Warren et al. 2024). Coastal areas, where sugarcane is often grown due to their fertile soils and favourable climate, are particularly vulnerable to floods favoured by rising waters. Sugarcane is a crop sensitive to flooding, leading to root rot and a reduction in the quality and quantity of crops (Gomathi et al. 2015). A rise in sea level can also result in increased soil salinisation, making agricultural land less productive or even infertile. Therefore, some of the main producing regions, such as those located in deltas and coastal plains, could see their production decrease significantly.

13.4.2 Adaptation Pathways and Mitigation Potential of Sugarcane Cultivation

To cope with climate change, farmers will need to adopt effective technical adaptation and mitigation strategies but also review the geographical distribution of cultivated areas. One of the main technical adaptation pathways is the selection and cultivation of sugarcane varieties that are more resistant to drought, heat and diseases (Goebel and Sallam 2011; Grandis et al. 2024). In particular, drought resistance is seen as an essential characteristic to develop future varieties. An increase in the rooting depth and water use efficiency of varieties is a sought-after trait for these drought-tolerant varieties. The long (10–15 years) and costly varietal creation and selection programs, coupled with the improvement of agronomic practices on these improved varieties, play a crucial role.

Optimising irrigation is also essential in many regions of the world. Drip irrigation techniques, for example, allow for more efficient use of water, reducing losses through evaporation and ensuring that plants receive the necessary moisture during periods of drought. Moreover, practices limiting evaporation such as mulching can improve water retention, thus increasing the resilience of crops to climate variations.

Another adaptation pathway, more specific to certain regions, involves shifting crops to regions that have become more favourable for sugarcane cultivation in connection with the increase in temperatures or the adaptation of varieties (Poser et al. 2020). For example, high-altitude areas in the tropical islands of the Indian Ocean will be more favourable for sugarcane cultivation even under non-irrigated conditions (Christina et al. 2024). Also, a shift in the harvest period in certain regions like the north of South Africa has shown potential to improve yield in the future (Park et al. 2007). Consequently, there is already an increased interest in sugarcane in historically low-producing regions, such as southern Europe for example.

Crop diversification is another adaptation strategy, particularly for small-scale farmers. By integrating complementary crops, farmers can reduce their dependence on a single crop, thus diversifying their sources of income and improving the resilience of their farms to climate hazards (Aurand et al. 2022). Furthermore, the development of sustainable agroecological practices, such as crop associations, can help maintain long-term land productivity by improving soil structure, increasing biodiversity and reducing erosion, while decreasing pesticide use (Soulé et al. 2024), thus contributing to the reduction of GHG emissions.

Moreover, sugarcane crops can play a significant role in mitigating climate change through several mechanisms, including soil carbon storage, but also through a direct impact on the local climate (Loarie et al. 2011). Sugarcane has a dense and deep root system, which allows for effective soil carbon sequestration (see Chap. 17), compared to other crops (La Scala Junior et al. 2012). For example, a study in Brazil estimated that 2.4 t/ha of CO₂ was emitted during a one-year sugarcane cultivation cycle (de Figueiredo et al. 2010), which is less than the amount of carbon present in the sugarcane roots at harvest (2–6 t/ha of organic carbon) (Chevalier et al. 2023). In addition, sugarcane is often used to produce biomass and bioethanol

(see Chap. 19), alternatives to fossil fuels that help reduce GHG emissions. Initiatives aimed at reducing GHG emissions from sugarcane production can also contribute to climate change mitigation. In particular, the use of sugarcane residues for bioenergy production and improving energy efficiency in the transformation processes are examples of measures that can reduce the carbon footprint of the sector (Cherubin et al. 2021). The same applies to water savings made in the factory and in the fields.

In conclusion, climate change poses significant challenges for sugarcane cultivation, but adaptation strategies exist, and this crop has a strong potential for mitigation through carbon storage *via* its deep root system. By combining agronomic innovation, sustainable farming practices, and the necessary political support for the transition, it is possible to strengthen the resilience of sugarcane to climate impacts and ensure the sustainability of this essential sector for many national economies. However, small-scale farmers, who account for a large part of global sugarcane production, are particularly vulnerable to climate change. Therefore, government policies and investments in agricultural infrastructure, such as water management systems and support programs for small-scale farmers, are essential to strengthen the resilience of the crop.

13.5 Cotton in the Face of Climate Change

Edward Gérardaux, Bruno Bachelier, and Romain Loison

Cirad, UPR Agroecology and Sustainable Intensification of Annual Crops (Aïda), Montpellier, France

Aïda, Univ. Montpellier, Cirad, Montpellier, France

13.5.1 *The Global Cotton Sector: A Distribution Across Five Continents with Significant Disparities*

With an annual production of over 24 Mt., cotton has been the leading natural fibre and the second textile fibre in volume, behind synthetic fibres, for several decades. In 2022–2023, two-thirds of the world's cotton fibre production came from the Asia-Oceania region, a quarter was produced on the American continent and less than a tenth in Africa.

The average global yield of 800 kg of fibre per hectare hides large disparities between production areas. Thus, while Australia obtains more than 2000 kg/ha, Africa only produces an average of 400 kg/ha. This gap reflects the diversity of abiotic, biotic, technical and organisational conditions of cotton production. In practical terms, the spectrum ranges from small-scale, low-mechanisation family farming in the South to intensive farming in developed countries.

In cotton-growing countries where cultivation is not intensive, cotton is mainly grown in small family farms, on a few hectares, almost exclusively rainfed, with small-scale mechanisation, rarely motorised. Harvesting is still largely manual, which is a constraint due to labour shortages. Food crops (legumes, cereals, etc.) are rotated in the cropping system and some benefit from the residual effect of cotton fertilisation. Depending on the production areas, either the producers source inputs from the local market and sell their harvest to collectors (Asia) or the producers contract with a cotton company, public or private, which provides them with inputs on credit at the beginning of the season and guarantees the purchase of their harvest at a price set at the beginning of the season (Africa). Although providing a low margin to producers under these conditions, cotton cultivation is considered a cash crop, contributing significantly to the monetary income of several million families. In addition, there are tens of millions of people involved in the various stages of the sector, from production to processing.

In the most advanced countries (United States, Australia), cotton cultivation is practised by large farms, motorised from sowing to harvest, irrigated and intensive according to the principles of precision agriculture, and conducted using high-performance varieties, often transgenic. When they are not themselves ginners,⁵ the producers subcontract the primary processing of their harvest to private companies and remain owners of the fibre and seeds obtained, which they then sell to commercial intermediaries.

The secondary processing of cotton fibre into textiles has great difficulty developing locally in Africa, which exports nearly 90% of its production and thus loses almost all of the added value associated with textile products (yarn, fabric, clothing, etc.). In a century, it has significantly declined on other continents, mainly in favour of a few Asian countries, whose industries process more than 80% of global production. This strong concentration in countries with low labour costs allows the global market to be supplied with textiles, some of which feed the fast-fashion industry.

While the fibre represents three-quarters of the value of the harvest, the seed also contributes to the economy of the sector. It is an important oilseed source, most often valued locally in human (oil) and animal (cake) food, but also in cosmetics.

13.5.2 Impacts of Climate Change on Major Cotton Production Areas

As with all crops, climate change will have an effect on growth conditions, and therefore on yields and the sustainability of cotton industries. Thanks to several of its traits, cotton will respond differently compared to other crops. It is a plant resistant to drought and high temperatures, mainly due to its physiological characteristics.

⁵A ginner is a public or private entrepreneur responsible for ginning (or primary processing) of cottonseed (the product of cotton harvesting, composed of seeds bearing fibres) to separate the fibre from the seed.

- Firstly, its base temperature⁶ of 12 °C makes it a plant with high growth and functioning ranges: the optimum temperatures are between 27 °C and 32 °C for vegetative growth and between 24 °C and 27 °C for fruit development.
- Secondly, the indeterminate growth of cotton, which produces fruiting and vegetative organs concurrently throughout its cycle and has the ability to shed underdeveloped fruiting organs, gives it a certain plasticity. Thus, a period of high heat or moderate duration drought does not irreversibly affect production, as the plant will compensate by producing new fruiting organs once the stress is relieved.
- Thirdly, the root system of cotton is taprooted, allowing deep soil exploration and access to water up to 1.5 m deep.
- Fourthly, cotton is an anisohydric plant: it does not close its stomata during moderate water deficits. This characteristic allows it to maintain photosynthesis to produce more roots, explore more soil and access deeper water resources, in relation to the previous characteristic.

It is also a so-called C3 plant,⁷ less efficient in terms of CO₂ than C4 plants, many of which are found in tropical regions (maize, sorghum, sugarcane, etc.). Therefore, an increase in atmospheric carbon will be very favourable to cotton (Mauney et al. 1994).

For all these reasons, climate changes will have less negative effects on cotton than on other plants, especially if water resources are available through irrigation, abundant rainfall or deep water tables. On the other hand, under strict and limiting rainfed conditions, such as in the cotton-growing areas of semi-arid and sub-humid Africa, negative effects of high temperatures are to be feared. They will only be offset by the enrichment of atmospheric CO₂ if rainfall is sufficient.

In China, the current leading global producer, the effects of climate change will on average be negative, with regional disparities: negative in the Yangtze valley and neutral or positive in the north-west regions and the Yellow River (Chen et al. 2015).

In the United States, cotton is grown in the southern states. The forecasts of the effects of climate change there are mixed between yield losses and gains (Sharma et al. 2022), due to a negative effect of an increase in the frequencies of extreme events and a positive effect of the rise in CO₂ and precipitation.

Scientific studies of the effects of climate change in sub-Saharan Africa are scarce. The major cotton production basins are the Sudanian and Sudano-Sahelian zones of West and Central Africa. The IPCC forecasts show contrasting situations between the west and the east. Rainfall deficits in Senegal, Mali and Burkina Faso will cause yield decreases. On the other hand, increases in rainfall in Nigeria, Cameroon and Chad, and uncertain intermediate situations between these two zones (Ivory Coast, Ghana, Benin, Togo) could allow for yield increases. In Benin, Amouzou et al. (2018) predicts variable effects, mostly positive, ranging between

⁶Base temperature (or zero vegetation): the temperature below which a crop cannot grow and develop.

⁷C3 plant: a plant whose photosynthetic mechanism is based on the production of three-carbon carbohydrates.

-7% and +41% on yields, while drawing attention to difficulties in soil nitrogen availability in case of high demand linked to the increase in biomass. Positive effects are also predicted in Cameroon (Gérardeaux et al. 2013).

In Europe, cotton is grown in Spain and in Greece with high yields thanks to irrigation and mechanisation. Low spring temperatures are a significant limiting factor for crop growth and global warming could bring favourable changes here. Adaptation of farming systems will be possible to take advantage of this (Engonopoulos et al. 2021). Moreover, water resources are in competition with the needs of the population. The crop could develop in countries further north such as France, Italy or Bulgaria.

In Australia, studies have shown contrasting effects on the yields and on fibre quality, even for rainfed cropping systems (Luo et al. 2016; Williams et al. 2015). Extreme events (droughts, floods, heatwaves) will become more frequent with more significant negative impacts.

In Central Asia, cotton is grown in plains subjected to very cold winters and very hot summers. The crops are irrigated, but water resources are already heavily exploited. Predictions of the effects of global warming include an increase in water demand and therefore a decrease in yields and cotton areas, which could disappear from certain zones (Schlubach 2021).

Finally, cotton is also produced in India: a decline in yields is expected in the North and neutral to positive effects in the central and southern parts (Hebbar et al. 2013). It is likely that yields will increase, but so will pest pressure.

In conclusion, without even considering possible adaptations, climate changes will not drastically alter the map and growing conditions of cotton. Some regions of the world will benefit, such as southern Europe, central Africa, southern India, and others will lose out, such as West Africa, Central Asia, northern India, the Yangtze valley in China.

13.5.3 The Paths of Adaptation and Mitigation of Cotton Cultivation in a Climate Change Context

Breeding associated with the choice of optimal sowing dates is an adaptive research activity that involves matching the growth phases of a crop to those of resource availability (Zimmermann et al. 2017). Moreover, a temperature increase of 2.5 °C will cause an acceleration of crop development and mechanically a shortening of the cycle of varieties by 5 days for flowering and 10 days for maturity. This can significantly disrupt the synchronism between periods when water needs are covered by rainfall. To counteract this effect, selection combined with the search for optimal sowing dates can adapt by choosing varieties with longer or shorter cycles, in order to bring flowering and maturity back to the desired dates (Wu et al. 2023).

In some cotton-growing areas, climate changes will create conditions favourable to cotton growth. But for these favourable conditions to result in yield improvement,

good plant nutrition must be ensured to hope for productivity gains. The biomass gains allowed by the favourable conditions must be covered by an improvement in the soil's nutrient supply. In the family farming systems of Africa, where access to the input market is limited and soils are fragile, it is highly likely that these potential gains will be nullified. One promising way to improve soil fertility without relying solely on external inputs is to practice agroecological farming systems, involving rotations or associations with legumes, buried or left on the soil to form a mulch of cover crops. Again, the capacities of small family farms to modify their farming systems, to access seed and agricultural equipment markets remain limited. The implementation of these adaptation paths will depend on public support policies.

Like most crops, cotton cultivation emits greenhouse gases through nitrogen inputs, fuel and electricity for tractors, irrigation, harvesters and ginning factories. It is estimated that 1.6 tonnes of GHGs are emitted to produce one ton of fibres (Hedayati et al. 2019). However, if we stop our balance at the year of production, the carbon stored in the fibres and in the roots is greater than that emitted to produce it. Unfortunately, over time, the carbon stored in the fibres is released into the atmosphere through the life cycle of the fabrics (Cotton Incorporated 2009). Research in agroforestry or agroecology aiming to improve the resilience of farming systems to climate changes by improving soil fertility and reducing dependence on synthetic nitrogen inputs also contributes to improving GHG balances. Experiments are underway all over the world, we can mention those conducted in the Desira-UE Innovac project in North Cameroon, which aim to qualify the effects of agroforestry parks on crop sustainability.

13.6 Conclusion: Tropical Crops Facing Climate Change, Knowledge to Share, Steps to Master, Governance to Rethink

Alexia Prades

Cirad, DGD-RS, Montpellier, France

The solutions recommended for food or commercial crops presented in this chapter are of three types. The first includes short-term solutions, often already adopted by farms: optimisation of water resource management, valorisation of local cultivated biodiversity, change in farming practices often including a shift towards agroecological systems, such as trials of innovative crop combinations. The second type of solution includes more radical measures, achievable in the medium term, such as moving production areas. Finally, certain long-term solutions rely, on varietal improvement combined with an increasingly refined understanding of plant functioning in a complex environment. Complexity arises from the use of several companion plants or agroforestry systems for example, to which is added the constraint of climate instability.

These three types of solutions are implemented at different time scales (see Chap. 20), but they do have one thing in common. All three are still under-researched, even though they have shown promising results (Côte et al. 2018). Actually, this research requires the mobilisation of coordinated multi-scale governance and support from public policies to catalize change and mitigate exposure to risk, especially for smallholders. Some of the solutions will disrupt the trajectories of entire territories and, in particular, their populations. Multidisciplinary and cross-value chains research will play a pivotal role for example, when studying certain forms of crop associations or replacing one crop with another. In addition, partnership research practices should be encouraged by mobilizing participatory approaches. The solutions exist and research actors, along with stakeholders, are ready to support the transformation of these territories. “Although they play a central role in feeding the planet, small producers only have access to 1.7% of climate action funding,” reminds the International Fund for Agricultural Development (IFAD), in an article published on its website on 4 April 2022. There is an urgent need to change our way of thinking, to modify our perspectives, our practices, our institutions and to finally trust small and medium scale producers who play a key role in the resilience of tropical territories facing climate change.

References

- Adam M, MacCarthy DS, Traoré PCS, Nenkam A, Freduah BS, Ly M, Adiku SGK (2020) Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: climate change or improved management practices? *Agric Syst* 185:102920. <https://doi.org/10.1016/j.agry.2020.102920>
- Adom F, Maes A, Workman C, Clayton-Nierderman Z, Thoma G, Shonnard D (2012) Regional carbon footprint analysis of dairy feeds for milk production in the USA. *Int J Life Cycle Assess* 17:520–534. <https://doi.org/10.1007/s11367-012-0386-y>
- Ahmadi N, Baroiller J-F, D’Cotta H, Morillon R (2015) Adaptation to salinity. In: Torquebiau E (coord) *Climate change and world agriculture*. Versailles, Quae editions, pp 50–62
- Amadou T, Falconnier GN, Mamoutou K, Georges S, Alassane BA, François A et al (2022) Farmers’ perception and adaptation strategies to climate change in Central Mali. *Weather Clim Soc* 14:95–112. <https://doi.org/10.1175/WCAS-D-21-0003.1>
- Amouzou KA, Naab JB, Lamers JPA, Borgemeister C, Becker M, Vlek PLG (2018) CROPGRO-cotton model for determining climate change impacts on yield, water- and N- use efficiencies of cotton in the dry savanna of West Africa. *Agric Syst* 165:85–96
- Aurand TC, Sunthornvarabhas J, Sriroth K (2022) Value addition through diversification of the sugar industry from farm to mill. *Sugar Tech* 24(4):1155–1166
- Carvalho AL d, Menezes RSC, Nóbrega RS, Pinto A d S, Ometto JPHB, von Randow C, Giarolla A (2015) Impact of climate changes on potential sugarcane yield in Pernambuco, northeastern region of Brazil. *Renew Energy* 78:26–34
- Chen C, Pang Y, Pan X, Zhang L (2015) Impacts of climate change on cotton yield in China from 1961 to 2010 based on provincial data. *J Meteorol Res* 29:515–524
- Cherubin MR, Carvalho JLN, Cerri CEP, Nogueira LAH, Souza GM, Cantarella H (2021) Land use and management effects on sustainable sugarcane-derived bioenergy. *Land* 10(1):72
- Chevalier L, Christina M, Février A, Jourdan C, Ramos M, Poultney D, Versini A (2023) Sugarcane responds to nitrogen fertilisation by reducing root biomass without modifying root accumula-

- tion. Presented at xxxi International Society of Sugar Cane Technologists (ISSCT) Congress, Hyderabad
- Christina M, Mézino M, Le Mézo L, Todoroff P (2024) Modelled impact of climate change on sugarcane yield in Réunion, a tropical Island. *Sugar Tech* 8:646
- Côte F-X, Poirier-Magona E, Perret S, Roudier P, Rapidel B, Thirion M-C (2018) The agro-ecological transition of agriculture in the south. Quæ editions., 368 p, Versailles. <https://doi.org/10.35690/978-2-7592-2824-9>
- Cotton Incorporated (2009) Summary of life cycle inventory data for cotton (Field to Bale—version 1.1–2 July 2009). Cotton Incorporated
- de Figueiredo EB, Panosso AR, Romão R, La Scala N (2010) Greenhouse gas emission associated with sugar production in southern Brazil. *Carbon Balance Manag* 53
- Defrance D, Sultan B, Castets M, Famien AM, Baron C (2020) Impact of climate change in West Africa on per capita cereal production in 2050. *Sustainability* 12:7585. <https://doi.org/10.3390/su12187585>
- Egonopoulos V, Kouneli V, Mavroeidis A, Karydogianni S, Beslemes D, Kakabouki I et al (2021) Cotton versus climate change: the case of Greek cotton production. *Notulae Botanicae Horti Agrobotanici Cluj-Napoca* 49:12547
- FAO (2025) FAOSTAT. <https://www.fao.org/faostat/en/#data/QCL>
- Faye B, Webber H, Naab JB, MacCarthy DS, Adam M, Ewert F et al (2018) Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. *Environ Res Lett* 13:034014. <https://doi.org/10.1088/1748-9326/aaab40>
- Gbenou GX, Assouma MH, Bastianelli D, Kiendrebeogo T, Bonnal L, Zampaligre N et al (2024) Supplementing zebu cattle with crop co-products helps to reduce enteric emissions in West Africa. *Arch Anim Nutr*:1–17. <https://doi.org/10.1080/1745039X.2024.2356326>
- Gérardeaux E, Sultan B, Palai O, Guiziou C, Oettli P, Naudin K (2013) Positive effect of climate change on cotton in 2050 by CO₂ enrichment and conservation agriculture in Cameroon. *Agron Sustain Dev* 33:485–495
- Goebel F-R, Sallam N (2011) New pest threats for sugarcane in the new bioeconomy and how to manage them. *Curr Opin Environ Sustain* 3(1–2):81–89
- Gomathi R, Rao PNG, Chandran K, Selvi A (2015) Adaptive responses of sugarcane to waterlogging stress: an overview. *Sugar Tech* 17(4):325–338
- Grandis A, Fortirer JS, Navarro BV, de Oliveira LP, Buckeridge MS (2024) Biotechnologies to improve sugarcane productivity in a climate change scenario. *Bioenergy Res* 17(1):1–26
- Hebbar KB, Venugopalan MV, Prakash AH, Aggarwal PK (2013) Simulating the impacts of climate change on cotton production in India. *Clim Chang* 118:701–713
- Hedayati M, Brock PM, Nachimuthu G, Schwenke G (2019) Farm-level strategies to reduce the life cycle greenhouse gas emissions of cotton production: an Australian perspective. *J Clean Prod* 212:974–985
- Impa SM, Perumal R, Bean SR, John Sunoj VS, Jagadish SVK (2019) Water deficit and heat stress induced alterations in grain physico-chemical characteristics and micronutrient composition in field grown grain sorghum. *J Cereal Sci* 86:124–131. <https://doi.org/10.1016/j.jcs.2019.01.013>
- IPCC (2021a) Climate change 2021—the physical science basis
- IPCC (2021b) Contribution to the sixth assessment report of the intergovernmental panel on climate change. Working Group I. <https://www.cambridge.org/core/books/climate-change-2021-the-physical-science-basis/415F29233B8BD19FB55F65E3DC67272B>
- Jones MR, Singels A, Ruane AC (2015) Simulated impacts of climate change on water use and yield of irrigated sugarcane in South Africa. *Agric Syst* 139:260–270
- Kuyah S, Muoni T, Bayala J, Chopin P, Dahlin AS, Hughes K et al (2023) Grain legumes and dryland cereals contribute to carbon sequestration in the drylands of Africa and South Asia. *Agric Ecosyst Environ* 355:108583. <https://doi.org/10.1016/j.agee.2023.108583>
- La Scala Junior N, De Figueiredo EB, Panosso AR (2012) A review on soil carbon accumulation due to the management change of major Brazilian agricultural activities. *Braz J Biol* 72(3):775–785

- Lafarge T, Julia C, Baldé A, Ahmadi N, Muller B, Dingkuhn M (2015) Rice adaptation strategy in response to heat at the flowering stage. In: Torquebiau E (coord) *Climate change and world agriculture*. Versailles, Quae editions, pp. 37–49
- Linnenluecke MK, Nucifora N, Thompson N (2018) Implications of climate change for the sugarcane industry. *WIREs Clim Change* 9(1):e498
- Loarie SR, Lobell DB, Asner GP, Mu Q, Field CB (2011) Direct impacts on local climate of sugarcane expansion in Brazil. *Nat Clim Chang* 1(2):105–109
- Luo Q, Bange M, Johnston D (2016) Environment and cotton fibre quality. *Clim Chang* 138:207–221
- Luquet D, Perrier L, Clément-Vidal A, Jaffuel S, Verdeil J-L, Roques S et al (2019) Genotypic covariations of traits underlying sorghum stem biomass production and quality and their regulations by water availability: insight from studies at organ and tissue levels. *GCB Bioenergy* 11:444–462. <https://doi.org/10.1111/gcbb.12571>
- Macedo IC, Seabra JE, Silva JE (2008) Greenhouse gas emissions in the production and use of ethanol from sugarcane in Brazil: the 2005/2006 averages and a prediction for 2020. *Biomass Bioenergy* 32(7):582–595
- Mauney JR, Kimball BA, Pinter PJ, LaMorte RL, Lewin KF, Nagy J, Hendrey GR (1994) Growth and yield of cotton in response to a free-air carbon dioxide enrichment (FACE) environment. *Agric For Meteorol* 70:49–67
- Park S, Howden M, Horan H (2007) Evaluating the impact of and capacity for adaptation to climate change on sectors in the sugar industry value chain in Australia. In: xxvi Congress, International Society of Sugar Cane Technologists, ICC, Durban, South Africa, 29 July–2 August 2007, pp 312–326
- Poser C, Barau L, Mézino M, Goebel F-R, Ruget F (2020) Effect of the germination threshold temperature on the geographical distribution of the variety R583 in Reunion Island. *Int Sugar J* 122(1461):640–657
- Rotundo JL, Salinas A, Gomara N, Borrás L, Messina C (2024) Maize outyielding sorghum under drought conditions helps explain land use changes in the US. *Field Crops Res* 308:109298. <https://doi.org/10.1016/j.fcr.2024.109298>
- Schlegel AJ, Lamm FR, Assefa Y, Stone LR (2018) Dryland corn and grain sorghum yield response to available soil water at planting. *Agron J* 110:236–245. <https://doi.org/10.2134/agronj2017.07.0398>
- Schlubach J (2021) Downscaling model in agriculture in Western Uzbekistan climatic trends and growth potential along field crops physiological tolerance to low and high temperatures. *Heliyon* 7:e07028
- Sharma RK, Kumar S, Vatta K, Dhillion J, Reddy KN (2022) Impact of recent climate change on cotton and soybean yields in the southeastern United States. *J Agric Food Res* 9:100348
- Sinha R, Soni P, Perret S (2020) Environmental and economic assessment of paddy based cropping systems in middle indo-Gangetic plains, India. *Environ Sustain Ind* 8:100067. <https://doi.org/10.1016/j.indic.2020.100067>
- Soulé M, Mansuy A, Chetty J, Auzoux S, Viaud P, Schwartz M et al (2024) Effect of crop management and climatic factors on weed control in sugarcane intercropping systems. *Field Crop Res* 306:109234
- Sourisseau J-M (2014) *Family farming and future worlds*. Quae editions, Versailles. 364 p
- Subbarao GV, Nakahara K, Ishikawa T, Ono H, Yoshida M, Yoshihashi T et al (2013) Biological nitrification inhibition (BNI) activity in sorghum and its characterisation. *Plant Soil* 366:243–259. <https://doi.org/10.1007/s11104-012-1419-9>
- Sultan B, Defrance D, Iizumi T (2019) Evidence of crop production losses in West Africa due to historical global warming in two crop models. *Sci Rep* 9:1–15. <https://doi.org/10.1038/s41598-019-49167-0>
- Thomas HL, Pot D, Jaffuel S, Verdeil J-L, Baptiste C, Bonnal L et al (2021) Mobilising sorghum genetic diversity: biochemical and histological-assisted design of a stem ideotype for biomethane production. *GCB Bioenergy* 13:1874–1893. <https://doi.org/10.1111/gcbb.12886>

- Tongwane M, Mdlambuzi T, Moeletsi M, Tsubo M, Mliswa V, Grootboom L (2016) Greenhouse gas emissions from different crop production and management practices in South Africa. *Environ Dev* 19:23–35
- Traore A, Falconnier GN, Couédel A, Sultan B, Chimonyo VGP, Adam M, Affholder F (2023) Sustainable intensification of sorghum-based cropping systems in semi-arid sub-Saharan Africa: the role of improved varieties, mineral fertiliser, and legume integration. *Field Crops Res* 304:109180. <https://doi.org/10.1016/j.fcr.2023.109180>
- Trébuil G, Hossain M (2004) Rice, ecological and economic challenges. Belin, Paris. 263 p
- Tuong TP, Bouman BAM (2003) Rice production in water-scarce environments. In: Kijne JW, Barker R, Molden D (eds) *Water productivity in agriculture: limits and opportunities for improvement*. CABI Publishing, pp 53–67. <https://www.cabidigitallibrary.org/doi/pdf/10.1079/9780851996691.0053>
- Warren R, Price J, Forstenhäusler N, Andrews O, Brown S, Ebi K et al (2024) Risks associated with global warming of 1.5 to 4 °C above pre-industrial levels in human and natural systems in six countries. *Clim Chang* 177(3):48
- Williams A, White N, Mushtaq S, Cockfield G, Power B, Kouadio L (2015) Quantifying the response of cotton production in eastern Australia to climate change. *Clim Chang* 129:183–196
- Wu F, Guo S, Huang W, Han Y, Wang Z, Feng L et al (2023) Adaptation of cotton production to climate change by sowing date optimisation and precision resource management. *Ind Crop Prod* 203:117167
- Zimmermann A, Webber H, Zhao G, Ewert F, Kros J, Wolf J et al (2017) Climate change impacts on crop yields, land use and environment in response to crop sowing dates and thermal time requirements. *Agric Syst* 157:81–92

Open Access This chapter is licensed under the terms of the Creative Commons Attribution-NonCommercial-NoDerivatives 4.0 International License (<http://creativecommons.org/licenses/by-nc-nd/4.0/>), which permits any noncommercial use, sharing, distribution and reproduction in any medium or format, as long as you give appropriate credit to the original author(s) and the source, provide a link to the Creative Commons license and indicate if you modified the licensed material. You do not have permission under this license to share adapted material derived from this chapter or parts of it.

The images or other third party material in this chapter are included in the chapter's Creative Commons license, unless indicated otherwise in a credit line to the material. If material is not included in the chapter's Creative Commons license and your intended use is not permitted by statutory regulation or exceeds the permitted use, you will need to obtain permission directly from the copyright holder.

