Review of crop modelling approaches to address climate change challenges in Africa

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Abstract. Africa is facing an urgent need to increase food production to meet increasing demands. Targeted investments in integrated agriculture and, water management systems are required to meet this challenge. However, there is a lack of comprehensive information on the potential applications of climate-smart agriculture (CSA). This paper reviews current crop modeling technologies and their applications within the scope of climate change and the CSA framework in Africa. It evaluates current research trends in various crop simulation models and suggest advanced approaches to improve crop and environmental assessment, crop management, and decision-making. A total of 140 relevant papers were considered. Results showed that 84% of studies used process-based models, with Maize being the most studied crop. Additionally, DSSAT crop models and analysis of variance models have the highest contribution of physical and empirical crop modeling studies respectively. Over 72% of studies have contributed to adaptation strategies and reducing yield gaps, while only 8% of studies have been conducted on climate change mitigation and their trade-offs with adaptation using crop models under CSA. To ensure food security through sustainable agricultural practices in Africa, there is crucial to implement CSA models with a focus on the climate change mitigation component.

Keywords: Crop models, Climate-Smart Agriculture, Climate change, Irrigation, Africa

1 Introduction

Agriculture in Africa is primarily rainfed, rendering the continent's agricultural sector very sensitive to climate change, fluctuating climatic conditions, and crop losses due to extreme weather events [1]. The impact of climate change is already affecting agricultural productivity, particularly among impoverished smallholder farmers [2]. Across the African continent, less than six percent of agricultural land is irrigated. For the next years, the demand for water will keep on rising to sustain productivity increases [3].The adoption of climate-smart agriculture might greatly enhance the agricultural sector by assisting African farmers in maximizing the potential pent up inside the small-scale agricultural system [4].Crop modeling supports agriculture in multiple capacities. They contribute to the comprehension of the interactions between the environment, crop, and soil, as well as pest management and natural resource management. Their contribution extends to evaluate the climate change impact on crop productivity, identify low-performing areas, and recommend agronomic practices to enhance profitability while promoting soil carbon storage [5, 6].

The core objective of this study is to offer an overview of the crop modeling technologies and their applications within the climate change context and the CSA framework in Africa, evaluate recent research advances in various crop growth simulation models, identify research gaps, and propose refined approaches to address climate change issues and sustain food security targets.

The first part of the study is dedicated to the systemic analysis of crop modelling studies in Africa by examining the distribution of modelling approaches deployed and identifying crop models used to meet major agricultural challenges of climate change. The second part discusses the crop models applications followed by outlining research needs and proposing potential improvements.

2 Selections of literature

Considering the present situation of the African agricultural sector and the crucial role of crop modeling tools in improving climate change mitigation and adaptation measures and promoting climate-smart agriculture targets, the systematic review answers the following questions: What is the recent status of crop modeling in the climate change context in Africa? The current gaps and research need in crop modeling, climate change adaptation, and mitigation in the climate-smart agriculture framework? And which opportunities and guidelines exist to address future research needs.

Figure 1 illustrates general screening approaches and flow of identifying relevant literature which provides a detailed overview of the methodology used in this study. This technique was intended to evaluate systematic reviews that provide more efficient and less biased data. for scientists, stakeholders, and decision-makers.

The articles used in this work were obtained through the Web of Science and the Scopus databases using the following keywords to refine the articles reviewed: “Crop modeling”, “Climate change”, “Adaptation”, “Mitigation”, “Climate-Smart agriculture”, and “Africa”.

The review focuses on crop modeling studies on the African continent, the key words selected in figure 1 has helped to limit the scientific articles examined between 2000 and 2022 which is the period that includes most of the modeling studies.

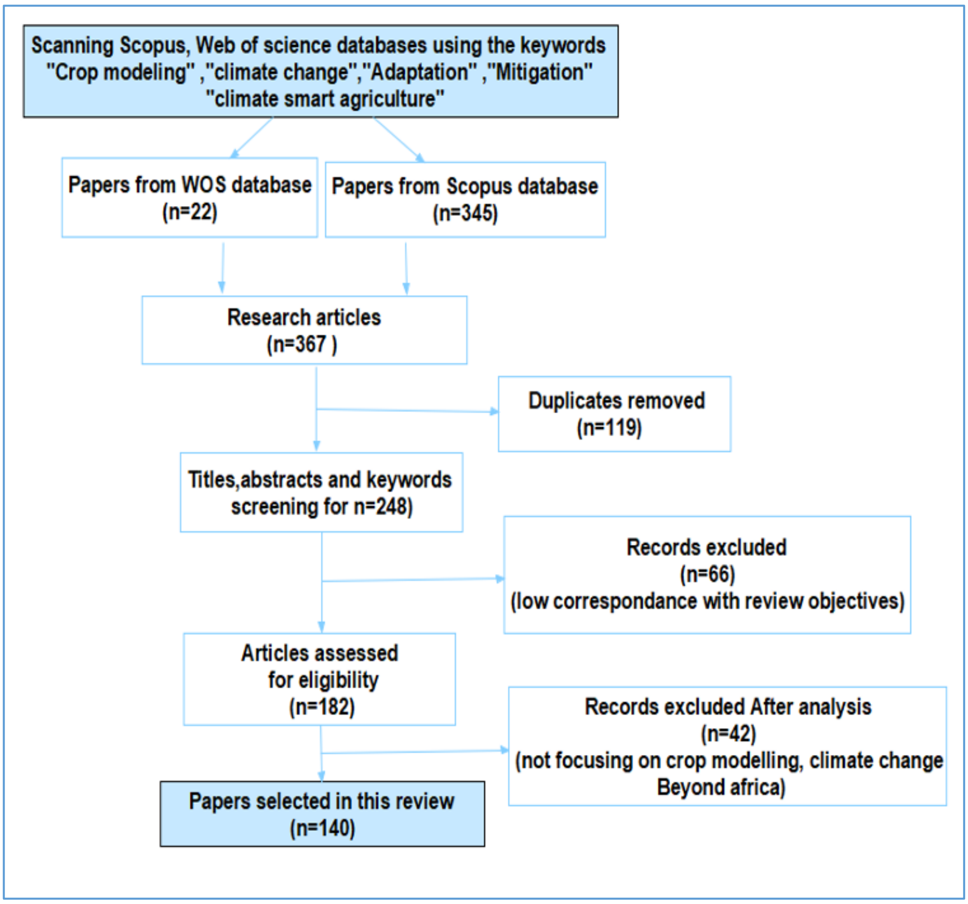

Fig.1 Flowchart for the selection of literature

Following the initial results, 345 articles were identified from searching on Scopus, and 22 papers were obtained on the Web of Science.

After deleting gray literature, presentations, keynotes, book chapters, non-English language papers, and extended abstract, the number of publications was limited to 248 articles left for further abstract and title scanning. In addition, some research articles were excluded due to low correspondence with the review objectives or the similarity of articles. Keeping the aim of this study, 140 relevant articles were selected and analyzed.

A full list of related papers was obtained for further analysis. The synthesis process involved extracting and classifying pertinent data from selected papers to obtain conclusions. Data extraction technique includes determining and collecting pertinent data from the selected articles, such as (research objectives, major outcomes, research limits, model employed and required inputs, and calibration process).

3 Results and discussion

3.1 Distribution of empirical and physical crop modelling studies in Africa:

Figure 2 describes the frequency distribution of physical and empirical crop models. Process-based crop models and empirical crop model studies accounted for 84% and 16% of these studies respectively, several crop modeling research in Africa employ process-based crop simulation models, such as DSSAT, APSIM, AquaCrop, and CROPSYST, due to their ability to simulate the effect of climate, soil, and crop management on crop development and predict potential yield. They are also well adapted to African agroclimatic conditions, as they can simulate a wide range of crops, soils, and climates.

Analysis of variance, regression, and Pearson correlation models are widely employed due to their robustness and effectiveness in providing detailed information about variable relationships, contributing to reduced uncertainty. However, there is still a risk of introducing bias if important elements of the system are excluded by extrapolation of correlative relationships beyond the bounds of observed variability.

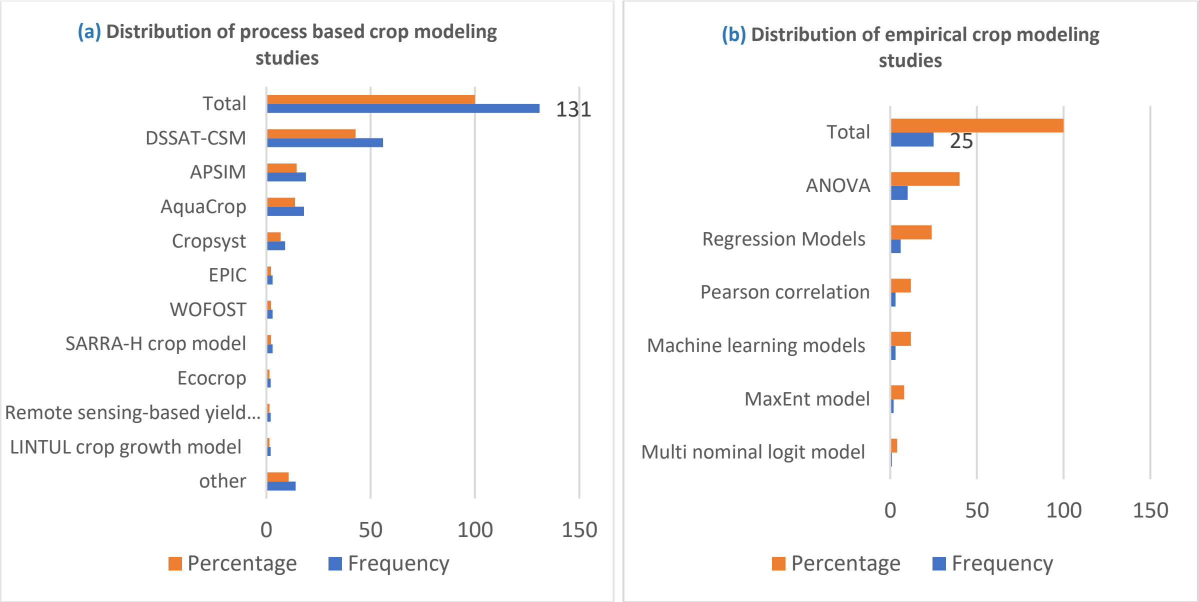

Fig. 2. Frequency distribution for studies employing (a) Process-based, and (b) Empirical approaches.

The physical models rely on an explicit description of system behaviour based on the simulation of physical processes, where the empirical modelling approach involves correlative relationships in accordance with the mechanistic understanding, without a full description of system dynamics [7]

The study revealed that maize is the most frequently used crop in climate change modelling studies in Africa. Despite its significant impact on food security and its adaptability to diverse soils and climates [8], maize has received less attention in climate change-related crop modeling studies in Morocco over the past decade compared to wheat, as indicated by the results.

3.2 Crop modeling applications in Africa

Researchers used crop modeling tools to explore how crops respond to various environmental circumstances, including temperature, rainfall, soil characteristics, nutrient supply, and irrigation on the African continent. Figure 3 indicates that crop modeling studies are focusing primarily on climate change adaptation strategies. The most used adaptation strategies are water and nutrient management, shifting planting dates, and incorporating new varieties, which are the important factors affecting crop yield. For example, Planting date shifting has been tested by several crop models in Africa as an adaptation practice to climate change for different crops including Sorghum

[9,10,11,12], Barley [13,14], Wheat [15,16,17,18], Maize [19,20,21,22,23,24], Quinoa [25], Potato [26], Cowpea [27], Groundnut [28], Teff and Pearl millet [29,30].

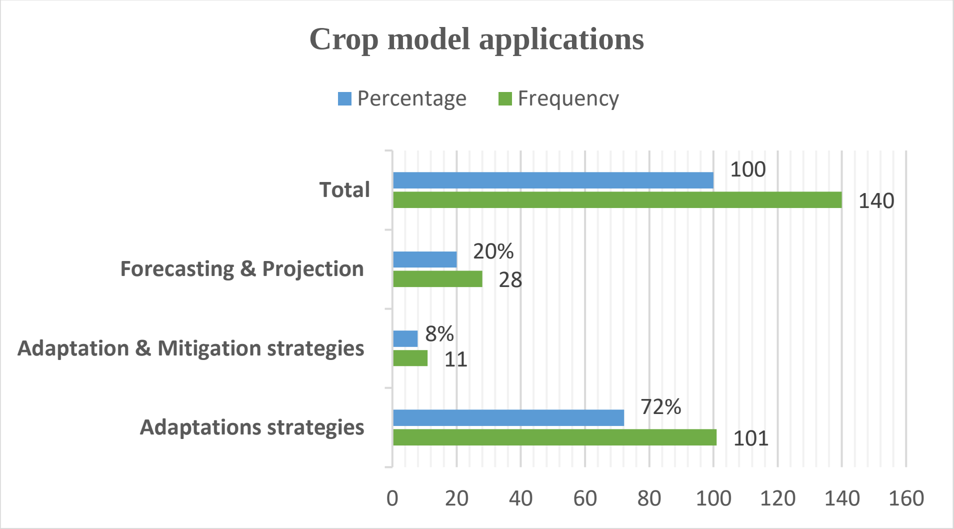

Fig.3. Crop model applications to address climate change effects in Africa.

However, only 8% of modeling studies have presented a co-benefit of climate change mitigation and adaptation strategies (figure 3), including climate-smart agriculture practices, deficit irrigation, conservative agriculture, and sustainable intensification approaches.

Adaptation is essential to reduce the harmful impact of Climatic variability and is considered an urgent and necessary measure in the African context, to protect crop production and sustain the continent's food security, improve the productivity of mainly subsistence crops, and reduce yield gaps.

African farmers are under increasing pressure to produce higher yields in the most vulnerable regions, the potential for implementing mitigation measures is rather low and adaptation is the major concern. On the other hand, reduced external input farming systems, which depend on the use of natural processes and organic fertilizer to ensure sufficient crop growth, reduce dependence on the supply of fertilizer and other inputs. In the long term, these systems are a valuable mitigation option that can enhance adaptation synchronously and that need to be developed locally[31].

4 Conclusion

Climate change and food security are among the major current development challenges. Agricultural production shows large annual fluctuations, mainly related to weather conditions and erratic rainfall. Moreover, the agricultural sector is missing many opportunities for sustainable development because climate change mitigation strategies have not been considered. 72% of studies have contributed to adaptation strategies and reducing yield gaps in Africa, while only 8% of studies have been conducted on climate change mitigation and their trade-offs with adaptation using crop models under CSA. However, it is widely admitted that to attain food security goals through sustainable agricultural practices in Africa, implementing CSA models with a focus on the climate change mitigation component can greatly improve crop productivity, and farmers' incomes and help reduce greenhouse gas emissions.

5 References

[1] A. Challinor, T. Wheeler, C. Garforth, P. Craufurd, and A. Kassam, "Assessing the vulnerability of food crop systems in Africa to climate change," *Clim Change*, vol. 83, no. 3, pp. 381–399, Aug. 2007, doi: 10.1007/S10584-007-9249-0/METRICS.

[2] J. F. Morton, "The impact of climate change on smallholder and subsistence agriculture," *Proceedings of the National Academy of Sciences*, vol. 104, no. 50, pp. 19680–19685, Dec. 2007, doi: 10.1073/PNAS.0701855104.

[3] M. W. Rosegrant, C. Ringler, and T. Zhu, “Water for Agriculture: Maintaining Food Security under Growing Scarcity,” *https://doi.org/10.1146/annurev.environ.030308.090351*, vol. 34, pp. 205–222, Oct. 2009, doi: 10.1146/ANNUREV.ENVIRON.030308.090351.

[4] V. O. Abegunde, M. Sibanda, and A. Obi, “The Dynamics of Climate Change Adaptation in Sub-Saharan Africa: A Review of Climate-Smart Agriculture among Small-Scale Farmers,” *Climate 2019, Vol. 7, Page 132*, vol. 7, no. 11, p. 132, Nov. 2019, doi: 10.3390/CLI7110132.

[5] M. Reynolds *et al.*, “Role of Modelling in International Crop Research: Overview and Some Case Studies,” *Agronomy 2018, Vol. 8, Page 291*, vol. 8, no. 12, p. 291, Dec. 2018, doi: 10.3390/AGRONOMY8120291.

[6] S. Asseng, Y. Zhu, B. Basso, T. Wilson, and D. Cammarano, “Simulation Modeling: Applications in Cropping Systems,” *Encyclopedia of Agriculture and Food Systems*, pp. 102–112, Jan. 2014, doi: 10.1016/B978-0-444-52512-3.00233-3.

[7] H. D. Adams, A. Park Williams, C. Xu, S. A. Rauscher, X. Jiang, and N. G. McDowell, “Empirical and process-based approaches to climate-induced forest mortality models,” *Front Plant Sci*, vol. 4, no. NOV, p. 438, Nov. 2013, doi: 10.3389/FPLS.2013.00438/BIBTEX.

[8] G. N. Falconnier *et al.*, “Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa,” *Glob Chang Biol*, vol. 26, no. 10, pp. 5942–5964, Oct. 2020, doi: 10.1111/GCB.15261.

[9] F. Getachew, H. K. Bayabil, G. Hoogenboom, F. T. Teshome, and E. Zewdu, “Irrigation and shifting planting date as climate change adaptation strategies for sorghum,” *Agric Water Manag*, vol. 255, Sep. 2021, doi: 10.1016/j.agwat.2021.106988.

[10] A. Araya *et al.*, “Evaluating crop management options for sorghum, pearl millet and peanut to minimize risk under the projected midcentury climate scenario for different locations in Senegal,” *Clim Risk Manag*, vol. 36, Jan. 2022, doi: 10.1016/j.crm.2022.100436.

[11] F. M. Akinseye, H. A. Ajeigbe, P. C. S. Traore, S. O. Agele, B. Zemadim, and A. Whitbread, “Improving sorghum productivity under changing climatic conditions: A modelling approach,” *Field Crops Res*, vol. 246, Feb. 2020, doi: 10.1016/j.fcr.2019.107685.

[12] E. K. Huet, M. Adam, B. Traore, K. E. Giller, and K. Descheemaeker, “Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management in southern Mali,” *European Journal of Agronomy*, vol. 140, Oct. 2022, doi: 10.1016/j.eja.2022.126587.

[13] M. W. Gardi, E. Memic, E. Zewdu, and S. Graeff-Hönninger, “Simulating the effect of climate change on barley yield in Ethiopia with the DSSAT-CERES-Barley model,” *Agron J*, vol. 114, no. 2, pp. 1128–1145, Mar. 2022, doi: 10.1002/agj2.21005.

[14] D. Cammarano *et al.*, “The impact of climate change on barley yield in the Mediterranean basin,” *European Journal of Agronomy*, vol. 106, pp. 1–11, May 2019, doi: 10.1016/j.eja.2019.03.002.

[15] S. Belaqziz, S. Khabba, M. H. Kharrou, E. H. Bouras, S. Er-Raki, and A. Chehbouni, “Optimizing the sowing date to improve water management and wheat yield in a large irrigation scheme, through a remote sensing and an evolution strategy-based approach,” *Remote Sens (Basel)*, vol. 13, no. 18, Sep. 2021, doi: 10.3390/rs13183789.

[16] L. E. F. Dewenam, S. Er-Raki, J. Ezzahar, and A. Chehbouni, “Performance evaluation of the WOFOST model for estimating evapotranspiration, soil water content, grain yield and total above-ground biomass of winter wheat in tensift al haouz (Morocco): Application to yield gap estimation,” *Agronomy*, vol. 11, no. 12, Dec. 2021, doi: 10.3390/agronomy11122480.

[17] J. Toumi, S. Er-Raki, J. Ezzahar, S. Khabba, L. Jarlan, and A. Chehbouni, “Performance assessment of AquaCrop model for estimating evapotranspiration, soil water content and grain yield of winter wheat in Tensift Al Haouz (Morocco): Application to irrigation management,” *Agric Water Manag*, vol. 163, pp. 219–235, Jan. 2016, doi: 10.1016/j.agwat.2015.09.007.

[18] Y. Brouziyne, A. Abouabdillah, A. Hirich, R. Bouabid, R. Zaaboul, and L. Benaabidate, “Modeling sustainable adaptation strategies toward a climate-smart agriculture in a Mediterranean watershed under projected climate change scenarios,” *Agric Syst*, vol. 162, pp. 154–163, May 2018, doi: 10.1016/j.agsy.2018.01.024.

[19] M. G. M. Ali *et al.*, “Optimizing sowing window, cultivar choice, and plant density to boost maize yield under RCP8.5 climate scenario of CMIP5,” *Int J Biometeorol*, vol. 66, no. 5, pp. 971–985, May 2022, doi: 10.1007/s00484-022-02253-x.

[20] H. Mugiyo, T. Mhizha, V. G. P. Chimonyo, and T. Mabhaudhi, “Investigation of the optimum planting dates for maize varieties using a hybrid approach: A case of Hwedza, Zimbabwe,” *Heliyon*, vol. 7, no. 2, Feb. 2021, doi: 10.1016/j.heliyon.2021.e06109.

[21] A. M. Dilla, P. J. Smethurst, N. I. Huth, and K. M. Barry, “Plot-scale agroforestry modeling explores tree pruning and fertilizer interactions for maize production in a Faidherbia parkland,” *Forests*, vol. 11, no. 11, pp. 1–15, Nov. 2020, doi: 10.3390/f11111175.

[22] M. P. van Loon *et al.*, “Can yield variability be explained? Integrated assessment of maize yield gaps across smallholders in Ghana,” *Field Crops Res*, vol. 236, pp. 132–144, Apr. 2019, doi: 10.1016/j.fcr.2019.03.022.

[23] J. Wolf, K. Ouattara, and I. Supit, “Sowing rules for estimating rainfed yield potential of sorghum and maize in Burkina Faso,” *Agric For Meteorol*, vol. 214–215, pp. 208–218, Dec. 2015, doi: 10.1016/j.agrformet.2015.08.262.

[24] M. S. Babel and E. Turyatunga, “Evaluation of climate change impacts and adaptation measures for maize cultivation in the western Uganda agro-ecological zone,” *Theor Appl Climatol*, vol. 119, no. 1–2, pp. 239–254, Jan. 2015, doi: 10.1007/s00704-014-1097-z.

[25] J. Alvar-Beltrán, A. Gobin, S. Orlandini, A. Dao, and A. D. Marta, “Climate resilience of irrigated quinoa in semi-arid West Africa,” *Clim Res*, vol. 84, pp. 97–111, 2021, doi: 10.3354/cr01660.

[26] A. C. Franke, L. N. Muelelwa, and J. M. Steyn, “Impact of climate change on yield and water use efficiencies of potato in different production regions of South Africa,” *South African Journal of Plant and Soil*, vol. 37, no. 3, pp. 244–253, May 2020, doi: 10.1080/02571862.2020.1736345.

[27] V. G. P. Chimonyo, A. T. Modi, and T. Mabhaudhi, “Assessment of sorghum–cowpea intercrop system under water-limited conditions using a decision support tool,” *Water SA*, vol. 42, no. 2, pp. 316–327, Apr. 2016, doi: 10.4314/wsa.v42i2.15.

[28] P. Laux, G. Jäckel, R. M. Tingem, and H. Kunstmann, “Impact of climate change on agricultural productivity under rainfed conditions in Cameroon-A method to improve attainable crop yields by planting date adaptations,” *Agric For Meteorol*, vol. 150, no. 9, pp. 1258–1271, Aug. 2010, doi: 10.1016/j.agrformet.2010.05.008.

[29] F. A. Mihretie *et al.*, “Identifying low risk and profitable crop management practices for irrigated Teff production in northwestern Ethiopia,” *European Journal of Agronomy*, vol. 139, Sep. 2022, doi: 10.1016/j.eja.2022.126572.

[30] D. S. Maccarthy *et al.*, “Climate change impact and variability on cereal productivity among smallholder farmers under future production systems in west africa,” *Sustainability (Switzerland)*, vol. 13, no. 9, May 2021, doi: 10.3390/su13095191.

[31] Food and Agriculture Organization of the United Nations, “Climate change adaptation and mitigation in the food and agriculture sector,” Mar. 05, 2008. https://www.preventionweb.net/files/8314_HLC08bak1E.pdf (accessed Apr. 11, 2023).