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Climate change impacts and adaptation strategies for crops in West Africa: A systematic review

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Abstract

Agriculture in West Africa faces the challenge of meeting the rising demand for food as national incomes and populations increase while production becomes more uncertain due to climate change. Crop production models can provide helpful information on agricultural yields under a range of climate change scenarios and on the impact of adaptation strategies. Here, we report a systematic review of the impact of climate change on the yield of major staple crops in West Africa. Unlike earlier reviews we pay particular attention to the potential of common agricultural adaptation strategies (such as optimised planting dates, use of fertilisers and climate-resilient crop varieties) to mitigate the effects of climate change on crop yields. We systematically searched two databases for literature published between 2005 and 2020 and identified 35 relevant studies. We analysed yield changes of major staple crops (maize, sorghum, rice, millet, yam, cassava and groundnuts) caused by different climate change and field management scenarios. Yields declined by a median of 6% (-8% to +2% depending on the crop) due to climate change in all scenarios analysed. We show that the common adaptation strategies could increase crop yields affected by climate change by 13% (-4% to +19% depending on the strategy) as compared to business-as-usual field management practices, and that optimised planting dates and cultivars with longer crop cycle duration could in fact offset the negative effects of climate change on crop yields. Increased fertiliser use has not mitigated the impact of climate change on crops but could substantially increase yields now and in the future. Our results suggest that a combination of increased fertiliser use and adopting cropping practices that take advantage of favourable climate conditions have great potential to protect and enhance future crop production in West Africa.

Keywords: crop productivity, West Africa, climate change impacts, climate change adaptation

1 Introduction

Climate change has already affected West African agriculture through changes in rainfall patterns, characterised by strong inter-annual rainfall fluctuations, increased frequency of rainfall extremes and prolonged droughts (Salack *et al* 2016, Sultan *et al* 2019). Agriculture in West Africa is predominantly rain-fed and thus highly vulnerable to climate change and variability, making crop production uncertain (Zougmoré *et al* 2016, Sultan and Gaetani 2016). Uncertainty about future crop production creates uncertainty for the food system, with consequences for economic, health and socio-cultural systems (van Mil *et al* 2014). To prepare the food system for future challenges, it is important to project potential crop production changes under different climate and field management scenarios to inform adaptation planning.

Crop models can be used to estimate changes in future crop production based on the simulated response of crops to field management, weather and soil processes. However, projected crop yields vary considerably between crops and locations and are strongly influenced by a wide range of potential climate and field management scenarios. In addition, crop yield projections are influenced by uncertainties from model parameters and representation of biophysical processes in different crop models (Asseng *et al* 2013).

Systematic reviews and meta-analyses that summarise and compare results from existing studies are useful tools to illustrate the range of projections and draw conclusions from a review of existing knowledge. Previous reviews concerning the impacts of climate change on crops in West Africa and sub-Saharan Africa found mainly negative climate change impacts on important staple crops (Roudier *et al* 2011, Knox *et al* 2012). These reviews focused on the raw impact of climate on crops, with little attention to how farming practices could reduce these impacts. However, in a global review of climate change impact studies, Challinor et al. (2014) demonstrated the importance of considering adaptation strategies, which significantly increased projected crop yields. Similarly, Müller (2013) noted that many projections for Africa see the possibility of increased agricultural production under climate change, especially if appropriate adaptation measures are taken. In addition, many case studies in West Africa have concluded that common farming practices, which respond to environmental change, can significantly reduce the negative impacts of climate change (Sultan and Gaetani 2016, Adam *et al* 2020).

The effects of farming practices are highly location and context-specific. Practices that reduce negative climate change impacts on rainfed agriculture respond to shifts in precipitation and temperature, which can vary greatly in West Africa (Turco *et al* 2015). Soil fertility, which is generally low in West Africa, can also be an important factor for many farmers when choosing suitable farming practices (Stewart *et al* 2020). Moreover, farmers' adoption of field practices is driven by access to markets, information and inputs (Ouédraogo *et al* 2017). It is therefore important to synthesise evidence on agricultural adaptations at the regional level in order to capture some of these contextual factors.

In this study, we systematically searched and reviewed peer-reviewed literature on climate change impacts on the yields of major crops in West Africa with and without considering adaptation strategies. We drew on data from the reviewed studies to illustrate the range of climate change-induced yield changes of major crops in West Africa simulated under different climate change and field management scenarios. We then quantified the impact of common adaptation strategies on crop yields. Finally, the data was used to discuss climate change impacts on crops in West Africa and the potential of adaptation strategies to reduce climate stress and increase future crop production.

2 Methods

2.1 Literature search strategy

This review follows the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) guidelines (Moher *et al* 2009). We considered peer reviewed articles, books and book chapters published between January 1, 2005, and December 31, 2020, that examined the response of crops to climate change in West Africa with and without considering adaptation strategies. The studies were sourced from the databases Scopus and Web of Science Core Collection using specific key words, synonyms, search phrases and strategies which were unique to each data-base or portal to select studies (Text S1). As search engines and portals are sensitive to the order of search key words and bullion symbols, we used a range of different key words and bullion symbols.

2.2 Selection Criteria and Data Extraction

We focused primarily on evidence from studies that use process-based crop simulation models as these studies comprise most of the quantitative literature exploring climate adaptation (Lobell 2014). An overview of all Inclusion and exclusion criteria for each study can be seen in Table 1. The data extracted from the studies included crop type, crop yield, crop yield change due to climate change or farming practices, publication year, country or region, location or agro-ecological zone, climate change scenario, type of climate model, field management scenario, crop model and simulation period of the baseline and the projection scenario.

Table 1: Inclusion and exclusion criteria for the systematic literature review process.

Search checkpoints	**Acceptance criteria**	**Rejection criteria**
Initial search	Studies published in English and French	Studies published in other languages
	Projected climate change and climate scenarios	No change in climate and short-term seasonal climate data
	Crop yield change	Studies that report indicators or parameters others than crop yield
	Studies focused on the West African region	Studies focused on other regions
	Local, country and sub regional studies	Global and continental
Title and abstract screening	Focused on the selected crops	non-crop agricultural systems
	Modelling studies with quantitative outputs	Studies with qualitative outputs and studies reporting greenhouse experiments. Studies reporting non-quantitative outputs
Full paper review	Original studies	Qualitative literature review and discourse analysis
	Numerical crop yield or proportion of crop yield changes	Qualitative description of crop yield patterns

	Crop yield and changes under climate change	Yield and changes under farming practices only
	Yield change under different climate scenarios	Yield changes over different years
	Adaptation options under different climate scenarios	Adaptation options without different climate scenarios
	Detailed methodology	Insufficient details are provided on the methodology to carry out data analysis

2.3 Data analysis

Crops that had been investigated in at least three studies, including maize, sorghum, millet, rice, groundnut, yam, and cassava, were selected for data analysis. Relative changes in crop yields due to climate change were analysed under all scenarios examined in the studies. In addition, the impact of climate change on crop yields with and without adaptation strategies, as well as the impact of adaptation strategies on crop yields within the climate scenarios, were analysed.

2.3.1 Grouping of field management scenario into adaptation and business-as-usual scenarios

Because a variety of adaptation scenarios were used in the studies, we have pooled some scenarios to facilitate comparison across studies. The aggregated adaptation scenarios include increased fertiliser applications, optimised planting dates, and the use of climate-resilient cultivars with short or extended crop cycle lengths, high-yielding, and drought and heat tolerant traits. All simulated adaptation techniques are listed and described in Table 3.

Business-as-usual (BAU) scenarios were selected according to the following criteria: If the studies explicitly provided a BAU scenario, this was adopted. If no BAU scenario was defined, the BAU scenario was determined on the basis of the adaptation practice:

- Conventional or traditional crop varieties were selected as the BAU scenario when climate-resilient crop varieties were used as the adaptation practice.
- Non-optimal planting dates (i.e., too late, or too early planting) were selected as the BAU scenario when optimised planting dates were used as the adaptation practice.
- Low, or no fertiliser use was selected as the BAU scenario when increased fertiliser use was used as the adaptation practice.

2.3.2 Calculating the impact of climate change on crop yields

In most studies, the impact of climate change on crop yields was calculated using the relative change between crop yields simulated with historical climate data and crop yields simulated with different climate change scenarios. Alternatively, weather parameters from historical climate data were artificially changed to analyse the response of crops to gradually changing temperature, precipitation and CO_2. An important limitation of this method is that interactions between climate parameters are not considered. If no relative changes in crop yields due to climate change were given in the studies, these were calculated using the absolute yields given.

$CY = (YF - YB) / YB$ (1)

where *CY* is the relative change in yields due to climate change, *YB* is the yield for the baseline climate scenario, and *YF* is the yield for the future climate change scenario. We compared crop yield changes due to climate change based on the four representative concentration pathway scenarios (RCPs): RCP 2.6, RCP 4.5, RCP 6.0, RCP 8.5. When studies used temperature and emission scenarios to project crop yields, we allocated them to the best aligning RCP scenario using the mapping in Table S1. The climate scenarios used for each study are listed in Table S2.

2.3.3 Calculating the impact of climate change on crop yields with and without adaptation practices

We extracted or calculated the relative changes in crop yields due to climate change simulated under adaptation practices and under BAU practices.

$CY_m = (YF_m - YB_m) / YB_m$ (2)

where *CY* is the relative change in yields due to climate change for farming practice *m*, *YB* is the yield for the baseline climate scenario, and *YF* is the yield for the future climate change scenario. As the projected crop yields are compared to the baseline yields within the same field management scenarios, the impact of improved or more intensive farming practices on crop yields is excluded. The distributions of the relative crop yield changes are then compared between adaptation practices and corresponding BAU practices.

2.3.4 Calculating the impact of adaptation practices on crop yields within climate scenarios

We extracted or calculated the relative change between paired values of crop yields simulated with and without adaptation practices.

$MY_c = (YA_c - YBAU_c) / YBAU_c$ (3)

where *MY* is relative change in yields due to adaptation practices for the climate scenario *c*, *YA* is the yield for the adaptation practice, *YBAU* is the yield for the corresponding business-as-usual scenario. As changes in crop yields are compared within the same climate scenario, the impact of climate change on crop yields is excluded. The distributions of the relative changes in crop yields are then compared between baseline and future climate scenarios to analyse whether the effectiveness of adaptation practices changes in future climates.

2.3.5 Consideration of the variability of the results due to study-specific factors

In addition to the modelled field management practices, simulated crop yields are also influenced by other study-specific modelling factors. To indicate the sensitivity of calculated crop yield changes to study-specific factors, we compared the degree of variation in median crop yield changes due to climate change between different simulation periods, climate scenarios, field management scenarios, crop models, countries, agro-ecological zones and type of climate models. The degree of variation of the median crop yield changes is expressed by the Interquartile range (IQR) of all median values per factor (Figure S1 to S7).

3 Results

3.1 Screening

The initial database search resulted in 6204 articles from Scopus and Web of Science. After removing duplicates and screening for eligibility for the study based on the title and abstract, 245 articles remained. From a previously conducted theoretical literature search, four studies were added. Two studies were added after comments from two anonymous reviewers. After full article screening, a total of 35 articles remained from which the data presented in this study were extracted (Figure 1).

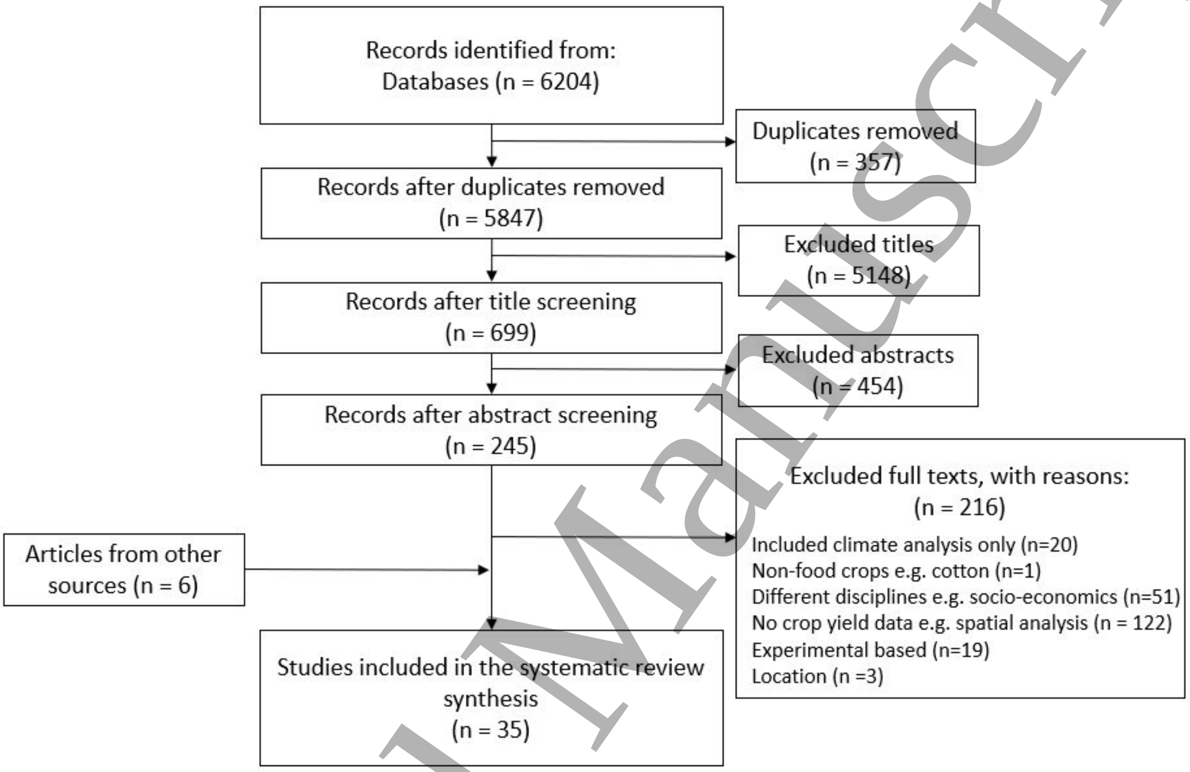

Figure 1: PRISMA diagram showing the number of articles at each stage of the screening process.

Table 2: Articles used in the systematic review on food system modelling in West Africa, 2005-2020

Article	*Author (Year)*	*Title*
1	Traore *et al* (2017)	*Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali*
2	Sultan *et al* (2014)	*Robust features of future climate change impacts on sorghum yields in West Africa*
3	Sultan *et al* (2013)	*Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa*
4	Singh *et al* (2017)	*An assessment of yield gains under climate change due to genetic modification of pearl millet*
5	Amouzou *et al* (2019)	*Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa*
6	Singh *et al* (2014)	*Quantifying potential benefits of drought and heat tolerance in rainy season sorghum for adapting to climate change*
7	Akumaga *et al* (2018)	*Utilizing Process-Based Modeling to Assess the Impact of Climate Change on Crop Yields and Adaptation Options in the Niger River Basin, West Africa*
8	Parkes *et al* (2018)	*Projected changes in crop yield mean and variability over West Africa in a world 1.5K warmer than the pre-industrial era*
9	MacCarthy *et al* (2017)	*Using CERES-Maize and ENSO as Decision Support Tools to Evaluate Climate-Sensitive Farm Management Practices for Maize Production in the Northern Regions of Ghana*
10	Yamoah (2018)	*Who Benefits, Who Loses and What can be done? - An Assessment of the Economic Impacts of Climate Change with and without Adaptation on Smallholder Farmers in Ghana*
11	Sarr and Camara (2018)	*Simulation of the impact of climate change on peanut yield in Senegal*
12	Regh *et al* (2014)	*Scenario-based simulations of the impacts of rainfall variability and management options on maize production in Benin*
13	van Oort and Zwart (2017)	*Impacts of climate change on rice production in Africa and causes of simulated yield changes*
14	Adam *et al* (2020)	*Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: Climate change or improved management practices?*
15	Adejuwon (2005)	*Assessing the suitability of the EPIC crop model for use in the study of impacts of climate variability and climate change in West Africa*
16	Adejuwon (2006)	*Food crop production in Nigeria. II. Potential effects of climate change*
17	Bosello *et al* (2017)	*Climate Change and Adaptation: The Case of Nigerian Agriculture*
18	Falconnier *et al* (2020)	*Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa*
19	Faye *et al* (2018)	*Potential impact of climate change on peanut yield in Senegal, West Africa*
20	Faye *et al* (2018b)	*Impacts of 1.5 versus 2.0 degrees C on cereal yields in the West African Sudan Savanna*
21	Freduah *et al* (2019)	*Sensitivity of maize yield in smallholder systems to climate scenarios in semi-arid regions of West Africa: Accounting for variability in farm management practices*
22	Guan *et al* (2015)	*What aspects of future rainfall changes matter for crop yields in West Africa?*
23	Mishra *et al* (2008)	*Sorghum yield prediction from seasonal rainfall forecasts in Burkina Faso*
24	Paeth *et al* (2008)	*Climate change and food security in tropical West Africa - A dynamic-statistical modelling approach*
25	Salack *et al* (2015)	*Crop-climate ensemble scenarios to improve risk assessment and resilience in the semi-arid regions of West Africa*
26	Srivastava *et al* (2015)	*Climate change impact and potential adaptation strategies under alternate climate scenarios for yam production in the sub-humid savannah zone of West Africa*
27	Tan *et al* (2010)	*Modeling to evaluate the response of savanna-derived cropland to warming-drying stress and nitrogen fertilizers*
28	Tingem *et al* (2009)	*Adaptation assessments for crop production in response to climate change in Cameroon*

29	Schleussner *et al* (2016)	*Differential climate impacts for policy-relevant limits to global warming: the case of 1.5 ◦C and 2 ◦C*
30	Tan *et al* (2009)	*Historical and simulated ecosystem carbon dynamics in Ghana: land use, management, and climate*
31	Hounnou *et al* (2019)	*Economy-Wide Effects of Climate Change in Benin: An Applied General Equilibrium Analysis*
32	Ahmed *et al* (2015)	*Potential Impact of Climate Change on Cereal Crop Yield in West Africa*
33	Srivastava *et al* (2012)	*The impact of climate change on Yam (Dioscorea alata) yield in the savanna zone of West Africa*
34	Tachie-Obeng *et al* (2013)	*Considering effective adaptation option to impacts of climate change for maize production in Ghana*
35	Raes *et al* (2021)	*Improved management may alleviate some but not all of the adverse effects of climate change on crop yields in smallholder farms in West Africa*

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3.2 The impact of climate change on crop yields

Most articles in Table 2 have analysed the impact of climate change on crop yields in Benin (10 articles) and Ghana (10), followed by Mali (9), Nigeria (7), Niger (6), Senegal (6), Burkina Faso (5) , Côte d'Ivoire (4), Cameroon (3), The Gambia (3), Mauritania (2), Togo (2), Chad (1), Guinea (1), Guinea-Bissau (1), and Sierra Leone (1). The crops analysed in most articles were maize (21 articles), sorghum (18), and millet (10). Other crops analysed in at least three articles were rice (8), groundnut (6), yam (5), and cassava (3). The most frequently used climate change scenario was the RCP8.5 scenario (19 articles), followed by the RCP4.5 scenario (16), the RCP6.0 scenario (11), and the RCP2.6 scenario (10).

Crop yields declined due to climate change by a median of 6% (25th to 75th percentile: -18% to +5%) in all scenarios analysed, with differences between individual crops. Median changes in crop yields were negative for maize (-6%; -18% to +4%), sorghum (-8%; -20% to +2%), rice (-6%; -19% to +5%), yam (-5%; -17% to +5%), cassava (-3%; -10% to +5%), and millet (-1%; -11% to +8%). Climate change impacts on groundnut yields were positive (+2%; -14% to +24%) (Figure 2a). The RCP 2.6 scenario led to the lowest change in yields of most crops. With higher radiative forcing, crop yield reductions became larger, and the variability of the changes increased (Figure 2b). Most crop yield projections covered the years between the 2020s and 2050s, while projections for the second half of the 21st century were limited in number (Figure 2c). A trend in the magnitude of crop yield changes over time could not be identified.

Overall, projected crop yield changes varied considerably, ranging from -97% to +268% as compared to the baseline. The projected crop yield responses to climate change are partly dependent on study-specific modelling factors (management scenario, simulation period, country, agro-ecological zone, climate model, climate scenario, crop model) (Figure 2d). The IQR of the median crop yield changes resulting from the different field management scenarios is highest, followed by the simulation period and the country of the study. The climate model, the climate scenario, the crop model, and the agro-ecological zone of the study side lead to lower IQRs of the median crop yield changes.

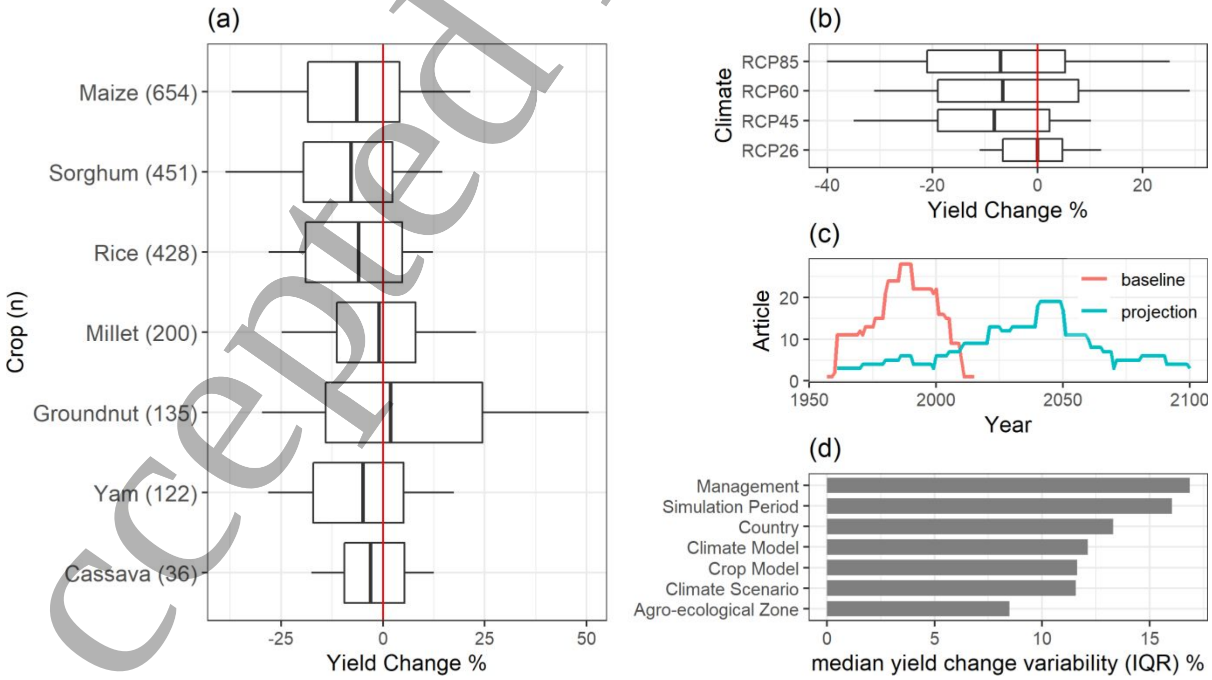

Figure 2: (a) Climate change impact on crops represented in at least three studies. Midline in each box represents median values of crop yield changes. Boxes include values from the 25th to the 75th percentiles and whiskers bracket values between the 10th and the 90th percentiles. (b) climate change impact on most common crops simulated with different climate scenarios. (c) Years covered per article for the baseline simulation period and the projection simulation period. (d) Degree of variation of median crop yield changes due to climate change impacts driven by study-specific factors for crop yield projections.

3.3 The impact of climate change on crop yields with and without adaptation practices

Among the most analysed strategies to mitigate the impact of climate change on crop yields was the increased use of fertilisers (10 articles), followed by the use of cultivars with extended crop cycle length (8), optimised planting dates (8), short-cycle cultivars (6), high-yielding cultivars (3), and drought- and heat-tolerant cultivars (2) (Table 3). Crop yields were projected to increase by 1% (25th to 75th percentile: -14% to +12%) due to climate change with adaptation strategies and decrease by 12% (-23% to 0%) without adaptation. Statistically significant positive effects of adaptation strategies on crop yield changes were found mainly in data from studies examining the impact of modified planting dates and extended crop cycle lengths on maize, rice and sorghum (Figure S8).

The impact of climate change on crop yields with and without individual adaptation strategies is illustrated in Figure 3. An extended crop cycle length was projected to increase crop yields by a median of 6% (25th to 75th percentile: 0% to +17%) under climate change, whereas yields of non-modified cultivars were projected to decrease by a median of 13% (-24% to -3%). Changing the planting dates led to a projected increase of crop yields by a median of 5% (0% to +20%) under climate change compared to a decrease of a median of 3% (-16% to +5%) under the business-as-usual scenario. The impact of other adaptation strategies on climate stress for crops were less significant in the studies analysed. Yields of short-cycle cultivars decreased by a median of 13% (-25% to -6%) and by 15% (-30% to -12%) when business-as-usual varieties are used. In studies where drought and heat tolerant cultivars were analysed, crop yields decreased by a median of 19% under climate change (-26% to -10%) compared to a 22% (-30% to -13%) reduction of yields from common cultivars. Yield declines due to climate change from high-yielding cultivars were slightly larger (-21%; -28% to -12%) than from the common cultivar (-17%; -29% to -13%). In fields with high fertiliser use, median crop yields decreased by 3% (-21% to +17%) and in fields with lower fertiliser use by 4% (-17% to +1%).

Table 3: Most common adaptation practices simulated in the reviewed studies

Adaptation practice	Description	Studies
Modified planting date	Shift of planting dates (earlier or later) for crops to coincide with altered seasonal rainfall distribution and thermal conditions.	Traore et al. 2017, Akumaga et al. 2018, MacCarthy et al. 2017, Regh et al. 2014, Adejuwon et al. 2006, Srivastava et al. 2015, Tingem et al. 2009, Tachie-Obeng 2013
Cultivar with short crop cycle	Short crop life cycles can reduce the risk of crops being exposed to the negative effects of intra-seasonal rainfall and temperature fluctuations.	Sultan et al. 2014, Singh et al. 2017, Singh et al. 2014, Guan et al. 2015, Mishra et al. 2008,

		Salack et al. 2015
Cultivar with extended crop cycle	Lengthening the life cycles of crops by increasing their thermal requirements helps to compensate for the shortening of the crop cycle duration as the temperature rises. This leaves more time for vegetative growth and grain formation.	Singh et al. 2017, Singh et al. 2014, Srivastava et al. 2015, Tingem et al. 2009, Mishra et al. 2008, Van Oort et al. 2017, Akumaga et al. 2018, Tachie-Obeng 2013
High-yielding cultivar	Hypothetical cultivar with increased yield potential traits such as radiation use efficiency, relative leaf size and partitioning of assimilates to the panicle.	Sultan et al. 2013, Singh et al. 2014, Singh et al. 2017
Drought and heat-tolerant cultivar	Hypothetical cultivar with higher rooting density and increased resistance against water and temperature stress during the most susceptible phenological phases.	Singh et al. 2017 Singh et al. 2014
Increasing fertiliser	Increased mineral and organic fertilisation reduces crop nutrient stress, which can influence the sensitivity of yields to climate change.	Akumaga et al. 2018, Srivastava et al. 2015, Adam et al. 2020, MacCarthy et al. 2017, Traore et al. 2017, Tan et al. 2009, Tan et al. 2010, Amouzou et al. 2019, Falconnier et al. 2020, Faye et al. 2018

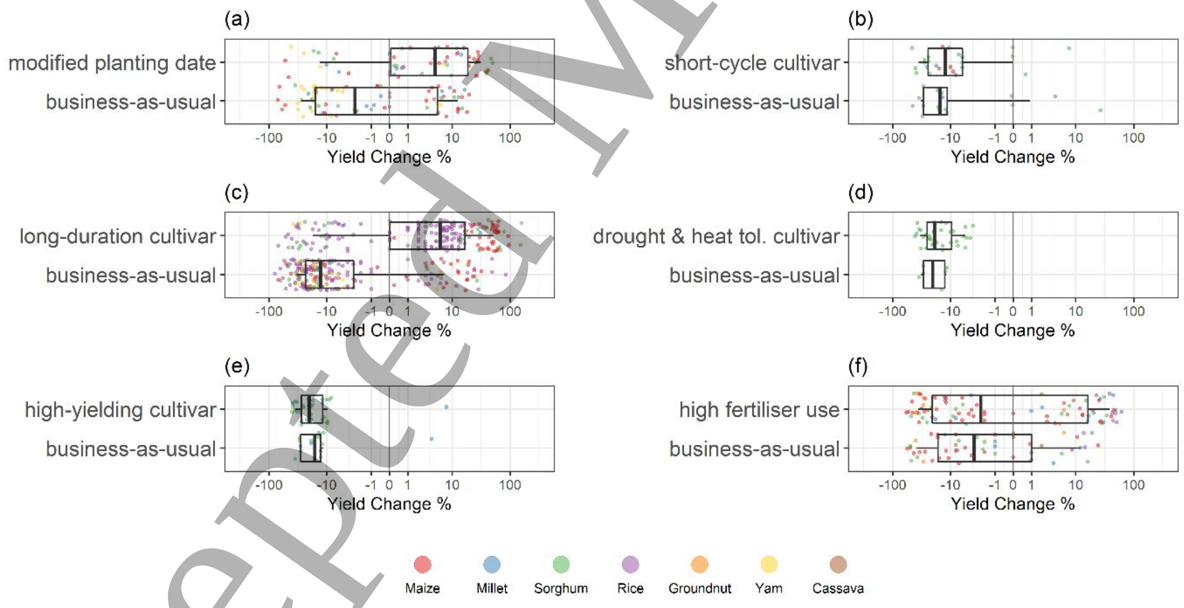

Figure 3: The impact of climate change on crop yields simulated under a business-as-usual field management scenario and simulated under an adaptation strategy scenario. All values have been log-transformed for better visual comparison. Plots for each crop are available in Figure S8.

3.4 The impact of adaptation practices on crop yields within climate scenarios

The amount of data available to analyse crop yield changes due to adaptation practices was lower than the amount of data available to analyse crop yield changes due to climate change. Many studies reported only relative changes in crop yields due to climate change, but not absolute crop yields for different adaptation practices or relative crop yield changes due to different adaptation practices. Due to the data limitations, statistically significant differences between the effect of adaptation practices in the future climate compared to the baseline climate were limited and could only be found for modified planting dates and drought- and heat-tolerant cultivars for sorghum and maize (Figure S9).

In most cases, the impacts of the adaptation practices were positive under both baseline and future climate scenarios (Figure 4). The positive effect of optimising planting dates on crop yields is greater under future climate (+37%; 25th to 75th percentile: +23% to +63%) than under baseline climate scenarios (+16%; +10% to +38%). Median values of positive crop yield changes for drought- and heat-tolerant cultivars are also larger under future climate scenarios (+6%; +5% to +7%) than under baseline climate scenario (+2%; +1% to +5%). This also applies to high-yielding cultivars, whose positive impact on yields vary between a median of +22% (+13% to +28%) and +17% (+11% to +38%) for future and baseline climate scenarios, respectively. Higher fertiliser use increased crop yields by a median of 62% (+50% to +105%) under baseline climates, which was substantially lower under future climates (+28%; +10% to +116%). The largest difference in the impact of adaptation measures between the baseline and future climate scenarios was found for cultivars with different crop cycle lengths. Long-duration cultivars increased crop yields by a median of 152% (+4% to +155%) under the baseline climate and by 30% (+7% to +147%) under the future climate. Short-cycle cultivars increased yields by 177% (-8% to +259%) under the baseline climate, but reduced yields by 21% (-29% to +310%) under future climates. The effect of different crop cycle durations on yields was very variable and based on a substantially smaller sample sizes compared to the other practices.

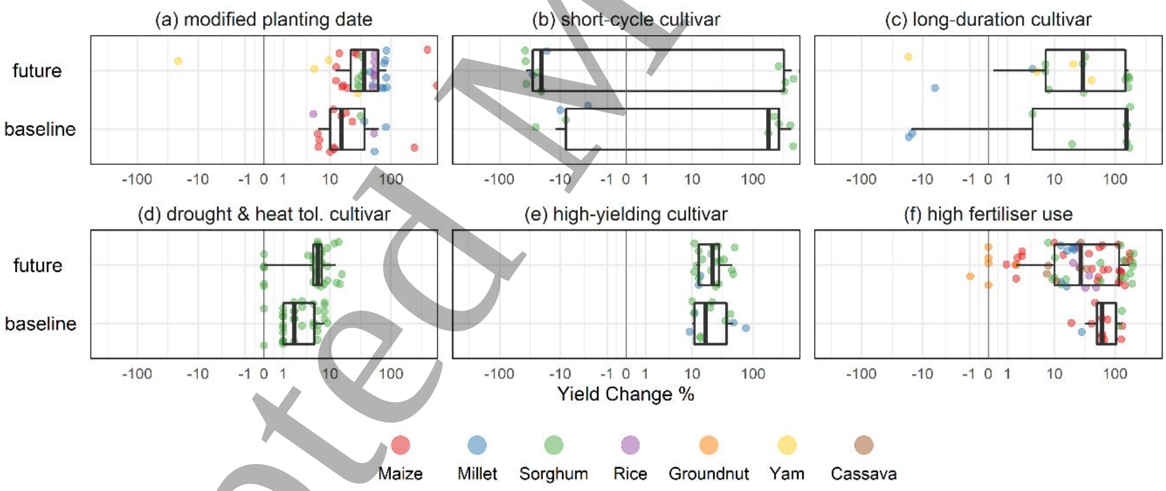

Figure 4: The impact of adaptation practices on crop yields within baseline and future climate scenarios, expressed by relative changes in crop yields between paired crop yield values simulated under an adaptation practice scenario and a business-as-usual scenario. All values have been log-transformed for better visual comparison. Plots for each crop are available in Figure S9.

4 Discussion

4.1 Climate change impacts on crops are predominantly negative in West Africa

The central tendencies of crop yield changes due to climate change were negative for maize, sorghum, millet, rice, yam and cassava. The negative impacts of climate change on crops in West Africa can be explained in part by the adverse role of higher temperatures, which shorten the duration of the crop cycle and increase evapotranspiration requirements (Sultan and Gaetani 2016). Previous studies confirm that climate change is having a predominantly negative impact on crops in West Africa (Jalloh *et al* 2013). Roudier et al. (2011) found a median yield loss of – 11% of important staple crops in West Africa. In a larger regional analysis, Knox et al. (2012) found mean yield changes of −17% (wheat), −5% (maize), −15% (sorghum) and −10% (millet) across Africa. As such, previous reviews quantifying changes in crop yields as a result of climate change indicate a greater decline in yields of most crops than found in this study. Although it is difficult to pinpoint the reason for this difference, our focus on agricultural adaptation strategies to mitigate the impact of climate change on crop yields may have contributed.

Groundnut was the least negatively affected by climate change. The positive changes in groundnut yields were mostly associated with CO_2 fertilisation in the studies reviewed (Tingem *et al* 2009, Faye *et al* 2018a). The benefits of CO_2 for crops are greatest for C3 crops such as groundnut and cassava. However, some of the most important staple crops in West Africa are C4 crops (e.g. maize, millet, sorghum), for which this positive effect is less significant (Roudier *et al* 2011).

Tuber and root crops are often considered less susceptible to climate change than other important staple crops in sub-Saharan Africa (Jarvis *et al* 2012). Many tuber and root crops have a high optimal temperature range that favours plant growth and are therefore less susceptible to the negative effects of warming (Srivastava *et al* 2015). Nevertheless, cassava and yam, were largely negatively affected by climate change in the studies reviewed. The yield changes for cassava and yam are based on the smallest sample size and are therefore more influenced by study-specific factors than the other crops. For example, the yam yield reductions were linked to a decrease in precipitation at the study site (Srivastava *et al* 2012, 2015).

However, future changes in precipitation patterns in West Africa are highly uncertain (Pendergrass *et al* 2017), and thus crop yield changes due to droughts and water availability are uncertain. Since West Africa is heavily influenced by summer monsoon rainfall, resulting in high variability in seasonal rainfall, uncertain wet or dry conditions are an important constraint to projecting crop yields in this region, especially since agriculture is mainly rain-fed (Ramirez-Villegas *et al* 2013, Guan *et al* 2015, Salack *et al* 2016). Studies analysing inter-annual yield variability and probability of yield failure can help to assess the resilience of crops in those environments (Guan *et al* 2017).

4.2 Adaptation strategies to offset negative climate change impacts

Despite the uncertain impacts of climate change on crops, previous studies concluded that the impacts of climate change on crops in West Africa will be largely negative without agricultural practices that respond to changing environmental conditions (Roudier *et al* 2011, Paeth *et al* 2008). This study showed that adaptation strategies can significantly reduce negative climate change impacts. A similar effect was found by a review of studies by Challinor et al. (2014), who found that adaptation increases simulated yields (wheat, rice, maize) in different temperate and tropical global regions by an average of 7-15%. This was confirmed by various ground studies that demonstrate the positive effect of climate-smart technologies and practices on crop yields in West Africa (Zougmoré *et al* 2014, 2018).

In most studies reviewed, climate resilient crop varieties and optimised planting dates led to higher yields compared to the business-as-usual scenario and could often offset the negative impacts of climate change for crops. However, the impact of these adaptation techniques on the response of crops to changing climate differs widely and can be negative.

The impact of climate-resilient crop varieties depends on how well they are matched to changing climate patterns. Whilst longer varieties with larger thermal requirements can produce higher yields in a warming climate (Singh *et al* 2014, Tingem *et al* 2009), varieties with a shorter crop cycle can protect against yield loss due to late season drought stress (Siebert and Ewert 2012). Similarly, location and context-specific circumstances are crucial for the selection of cultivars. At locations where water resources are scarce, cultivars with increased resistance to heat shocks and drought can be used (Debaeke *et al* 2017). Although these cultivars were less common in the studies reviewed and the few cases analysed had a small impact on reducing climate stress, drought- and heat-tolerant cultivars have been reported as an effective adaptation technique in arid and semi-arid tropical climate (Singh *et al* 2017, Segnon *et al* 2021).

Despite the benefits of modern climate-resilient varieties, certain traits of traditional varieties are also beneficial for crop resilience to future climate conditions (Sultan *et al* 2013). For example, traditional sorghum cultivars with a longer growth cycle could better take advantage of increased rainy season length and increased total rainfall amount than modern cultivars with a short growth cycle (Guan *et al* 2015). Photoperiod sensitivity, which is a common characteristic of traditional crop varieties, can shorten the plants reproductive phase through early flowering, thereby reducing climate stress from a shortening growing season due to warming (Daba *et al* 2016). In addition, with traditional photoperiod-sensitive varieties, farmers can more flexibly adjust their planting dates to the rainfall variability common in the arid regions of West Africa, thus taking advantage of early rains (Mishra *et al* 2008).

The impact of changing planting dates on crop yields is closely related to seasonal weather patterns. By changing the sowing dates, the developmental stages of the plants are adapted to the seasonal weather patterns that determine plant development, such as the beginning and end of the rainy season, the distribution of precipitation within the season or thermal conditions, which influences the duration of the vegetation and reproductive phase, as well as the timing of possible heat and drought stress (Regh *et al* 2014, Mishra *et al* 2008, Tingem *et al* 2009, Freduah *et al* 2019). In addition, the time of sowing influences crop yields by determining the timing of other management practices such as tillage, fertilisation and irrigation (Regh *et al* 2014).

Although optimised planting dates are in most cases an effective strategy to reduce and offset negative impacts of climate change on crop yields, this strategy did not offset the negative impacts of climate change on crop yields in all studies reviewed (Tingem *et al* 2009, Akumaga *et al* 2018, Srivastava *et al* 2015). Planting too early may lead to crop failure due to failed establishment, and delayed planting will shorten the overlap between plant growing season and rainfall season and thus yields (Mishra *et al* 2008, MacCarthy *et al* 2017). Moreover, shifting planting dates can cause logistical problems for farmers. Farmers might struggle to plant on time because of lack of machinery (Traore *et al* 2017), or shifting the sowing date of certain crops may lead to an overlap with the growing season of the next crop (van Oort *et al* 2016).

4.3 A combination of strategies is needed to increase crop yields in a changing climate

In several cases, the greatest potential of climate-resilient crop varieties and modified planting dates to offset climate change impacts was only achieved in combination with optimised fertiliser and irrigation management (Sultan *et al* 2013, Srivastava *et al* 2015, MacCarthy *et al* 2017). Despite the positive impact of fertiliser in combination with other adaptation practices on reducing climate impacts on crops, increasing fertiliser alone did not reduce climate stress for crops in most cases. Some studies even reported increased adverse climate impacts on crop yields in relative terms with higher fertiliser use (Faye *et al* 2018a, Sultan *et al* 2014). This is probably because with lower nutrient deficiencies, plants are more able to take advantage of good weather conditions and are therefore more sensitive to climate (Schlenker and Lobell 2010).

Whilst greater fertiliser use did not significantly reduce climate stress in most cases, it greatly increased crop yields under constant climate. Although this positive effect diminished in future climates, it was still substantial in many cases, showing the great potential of fertilisers to boost crop yields now and in the future. In several cases, where low fertiliser rates or soil fertility were the most severe constraint for production, the response of crop yields to fertiliser was stronger than to climate change (Tan *et al* 2009, 2010, Srivastava *et al* 2012).

Low soil nutrient levels due to low soil organic carbon content and poor availability of inorganic fertilisers are a common problem limiting crop yields in West Africa (Stewart *et al* 2020, Pradhan *et al* 2015, Zougmoré *et al* 2010). Thus, increasing availability and access to agricultural inputs should be part of the strategy to maintain or increase future crop production. In addition to nutrient deficiencies, constraints due to low farm inputs can also lead to water deficiencies and encroachment by weeds, pests and diseases, resulting in yield potential not being achieved (van Ittersum et al., 2016). As yield gaps are usually caused by multiple constraints, a combination of techniques is required to achieve potentially attainable yields at a site (Pradhan *et al* 2015).

4.4 Implications for policy and practice

Farmers in West Africa have experience in taking advantage of more favourable growing conditions by adopting a range of measures, such as shifting planting dates; changing species, varieties, and crop rotations; altering soil management and fertilisation; and introducing or expanding irrigation (Sultan and Gaetani 2016, Debaeke *et al* 2017, Segnon *et al* 2021). Although not all of these measures were addressed in the studies reviewed, it became clear that successful implementation of climate change adaptation strategies can be challenging and is highly dependent on site- and context-specific circumstances.

Shifting planting dates is often referred to as the simplest climate change adaptation strategy, and may be more accessible to many farmers than other strategies, such as improved varieties (Debaeke *et al* 2017, Singh *et al* 2017). As the timing of farm operations is often determined by a narrow rainfall band, optimal sowing dates require robust weather information (Tingem *et al* 2009, MacCarthy *et al* 2017). This is especially important in West Africa due to its high weather variability and the possibility of increasing variability due to climate change (Tarchiani *et al* 2018). Modified cultivars have been suggested as a valuable long-term climate change adaptation strategy (Tingem *et al* 2009). Breeding new varieties can take more than ten years (Asseng and Pannell 2013); thus, understanding future climatic conditions is important for developing varieties that are expected to be resilient under these conditions.

A challenge in the formulation of effective adaptation strategies is that the success of agricultural techniques to offset climate stress under the current climate does not necessarily mean that these strategies will work equally well for future climates (Lobell, 2014). Whilst the data analysed shows that the positive effect of optimised planting dates and drought- and heat-tolerant cultivars on crop yields can increase in future climates, this could not be confirmed for other adaptation practices. This was partly difficult to assess due to the small amount of data available, suggesting that further studies are needed to examine the effectiveness of adaptation strategies for future climates. Improving data quality for formulating long-term climate change adaptation strategies must be accompanied by improving regional climate models to better understand the future climate conditions to which farmers will have to adapt (Guan *et al* 2017). Crop diversification can spread risk against the current uncertainty of climate change impacts and provide a buffer for crop production against the impacts of greater climate variability and extreme events (Lin 2011, Segnon *et al* 2021).

The large yield gap in West Africa suggests enormous potential to increase agricultural productivity by shifting farming practices from traditional low-input farming to modern high-input farming. Much of the low productivity can be attributed to limited market access, resulting in reduced availability of fertilisers, pesticides, and machinery (Neumann *et al* 2010). Examples from Sub-Saharan Africa show that government subsidy programs for agricultural inputs can successfully improve land productivity (Wichelns 2003). In addition, farmers can significantly increase crop yields by investing in water harvesting methods and small-scale irrigation projects where water resources are available. While the potential for scaling up irrigation in West Africa is unclear, examples from low-income countries in Asia have shown that it is an essential component for increasing agricultural productivity and self-sufficiency (Headey and Jayne 2014). While increasing agricultural inputs and climate change adaptation measures hold great potential to maintain or increase future crop production in many regions, it will be important to avoid negative environmental impacts of intensification, particularly from overuse of nutrients and pesticides (van Ittersum *et al* 2016).

4.5 Limitations and strengths of this study

By reviewing studies examining the impact of climate change and adaptation strategies on crops we have shown the wide range of potential negative and positive changes in crop yields in West Africa. While much of the variation can be explained by differences between the studies reviewed, e.g., in field management assumptions and climate change scenarios, uncertainties in the simulation of climate change impacts on crops have also contributed.

Several authors have provided an overview of the limitations and necessary improvements of crop models and their application in climate change impact assessments (e.g., Boote et al., 2013; Ewert et al., 2015). Important uncertainties remain about crop responses to key climate parameters such as temperature (Asseng *et al* 2013), precipitation (Lobell and Burke 2008) and CO_2 (Ainsworth *et al* 2008, Long *et al* 2006). This leads to different physiological assumptions between crop models. In addition, crop models lack representation of the impacts of extreme weather events and of non-weather-related processes such as pests, diseases, and weeds, which may lead to an overestimation of the positive impacts of climate change on crops (Balkovič *et al* 2018, White *et al* 2011). Nevertheless, plant susceptibility to warming can be identified from known optimal temperature ranges that can control plant growth (Hatfield *et al* 2011). Due to similar basic assumptions about crop-temperature relationships in crop models, there is high agreement on negative impacts of climate change on most major staple crops at low latitudes, despite existing uncertainties (Rosenzweig *et al* 2014).

Although crop models are often used in assessing climate change impacts, they were originally developed to support field management decisions (Hertel and Lobell 2014). By focusing on this function of crop models, we illustrated that different field management assumptions lead to large differences in simulated climate change impacts on crops. Conversely, the varying effects of farming methods on crops are determined by climate scenarios and site-specific circumstances. A systematic review such as the one presented here can illustrate this variability and the potential of different farming practices to increase crop yields under a variety of scenarios and situations. Specific strategies to increase agricultural productivity and resilience in individual fields need to be explored based on detailed site information, in which locally parameterised and calibrated crop models can aid the decision-making process (Webber *et al* 2014).

An important limitation of this review is the small number of crops and adaptation techniques analysed (Figure S10). Since the impact of climate change varies greatly by crop and farming method, projections of production changes in West Africa become more robust as the number of crops and field management strategies considered increases. The lack of these data is partly because most climate adaptation studies are based on crop models, which are not yet suitable for all crops and have limited ability to simulate complex land management practices. Therefore, farming techniques that are widely used in West Africa, such as agroforestry or water harvesting through planting pits (*zai* or *half-moon*), were not considered in this study, although they are promising strategies to mitigate the negative impacts of climate change (Partey *et al* 2018, Zougmoré *et al* 2018). Furthermore, data on the impacts of climate change and adaptation strategies for fruits and vegetables are lacking. Given their importance to the agricultural sector in West Africa and their nutritional significance, this is an important concern that should be addressed in future climate adaptation studies.

5 Conclusion

In this systematic review we analysed the impact of climate change and adaptation practices on crop yields in West Africa and the potential of adaptation practices to offset negative climate change impacts. While recent studies suggest that climate change impacts are mostly negative, adaptation strategies that are already used by farmers can substantially mitigate these effects. Optimised planting dates and cultivars with an extended crop cycle length could offset negative climate change impacts in most cases. As the response of crops to different adaptation strategies varies widely, cultivation techniques must be carefully adapted to changing climate patterns and different conditions on individual farms. In addition to climate change impacts, the low productivity of West African agriculture deploys a huge potential to increase crop yields by transforming traditional low-input to modern high-input management systems. Although increased fertilisation has not reduced climate stress for crops in most studies, it can significantly increase crop yields in West Africa due to low soil productivity. As crop yields in West Africa are limited by many factors, a combination of methods is needed to increase crop production.

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Conflict of interest

The authors do not have any competing interests to declare.

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