Low-cost Adaptation Options to Support Green Growth in Agriculture, Water Resources, and Coastal Zones

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Abstract

The current and projected regional climate may strain investments in crop and livestock production systems, fisheries, and other water [natural] resources management in sub-Saharan Africa. Meanwhile, changes in some oceanic parameters across the Atlantic Ocean may lead to remarkably high vulnerability of coastal ecosystem, littorals, and the mangroves towards the mid-21st Century and beyond. Here, we identify the priority needs for adaptation and well-fitted adaptation options, deemed sustainable over the future climate, clean and low-cost in line with the countries' green economic emergence goals. Based on field evidence and customized simulation designs, the cost of these adaptation measures may likely decrease and benefit sustainable green growth in agriculture, water resources management, and coastal ecosystems of West Africa as hydroclimatic hazards grow to include pluviometric and thermal extremes. These adaption actions can be operationalized using sovereign wealth funds of governments, private sector investments, and scaled by global climate funds. However, their effectiveness requires sound policy, knowledge transfer, and relevant partnerships.

Introduction

Climate variability and change are becoming critical to the West African region in worsening food insecurity, natural resources degradation, and the vulnerability of socio-economic resources inland in the low-lying coastal areas. Although natural hazards such as landslides and climate-related diseases occur in the region, hydro-meteorological hazards such as floods and droughts remain the most dominant and devastating disaster events[1,2,3,4,5,6], exacerbating conflicts between farmers and pastoralists[7,8]. The projected changing climate may complicate all these patterns. Therefore, concerns over hunger, poverty, fragility, and disputes over scarce resources have contributed to fuelling the migration of the youth to Europe, as demonstrated by current trends in crossing the Mediterranean Sea. Therefore, the operational implementation of adaptation actions is the most crucial pathway for enabling private and governmental actors to respond to the impacts and explore and exploit climate change's transformative opportunities.

There are various adaptation options developed and applied by the local communities to reduce vulnerability, but many remain at a small scale demonstration initiatives[9,10,11,12]. Crop adaptation options include crop diversification and stress-tolerant vs. changes in cropping calendars, intercropping, organic and mineral manure[13,14,12], and soil water conservation techniques (*e.g.*, stone bunds, half-moon, Zai, etc.)[8], rainwater harvesting, improved irrigation techniques, and agroforestry[15,16,17]. Livestock adaptation strategies have been more concerned with breeding systems that include changes in practices such as diversification, intensification, and agro-pastoralism[8]. For fisheries, there is an upsurge in the search for new aquaculture species better adapted to the impacts of sea-level rise, fish pests, and diseases[18]. Meanwhile, several soft (*e.g.*, flood mapping) and rigid solutions (*e.g.*, construction of groins, seawalls, etc.) are designed and implemented in coastal areas to increase resilience to climate change impacts on coastal zones and low-lying areas[19,20]. Some non-structural adaptation measures include mostly income diversification through (re) organization of communities into cooperatives/associations, use of extension services (*e.g.*, market information systems, climate information advisory)[9,8,21], and other less climate-sensitive activities such as informal trading, temporary migration (rural-to-urban migration).

Despite this evident but informal and sluggish progress in adaptation and the widespread advances in technology worldwide, several challenges hamper the large-scale implementation of adaptation actions[22,23]. The weak technological developments in sub-Saharan Africa combined with capacity-building gaps and requirements have always been barriers to the practical and successful implementation of the National Adaptation Programmes of Action (https://unfccc.int/topics/adaptation-and-resilience/workstreams/national-adaptation-programmes-of-action-napa/publications-napas), the Nationally Appropriate Mitigation Actions (https://unfccc.int/topics/mitigation/resources/namas-technical-resources-and-publications) and the Nationally Determined Contributions (https://unfccc.int/process-and-meetings/the-paris-agreement/nationally-determined-contributions-ndcs/nationally-determined-contributions-ndcs).

In the specific case of West Africa, the countries lack the skills to formulate bankable and result-oriented climate actions from the national plans resulting in a regional inability to access both sovereign wealth funds and international climate finance to deliver technical services for adaptation to climate change (e.g., capacity development, policy research, and recommendations, project proposal development, etc.). With the increasing global arrangements for funding, operational implementation, monitoring, and evaluation of adaptation and mitigation actions[22,24], we update the fact and figures concerning climate change impact to inform the inter-sectoral priority needs, adaptation options, the costs for adaptation measures, and frameworks for sustainably mainstreaming these adaptation options in the green growth pace of the agricultural sector, water resources and coastal zones of West Africa.

Results

Pluviometric and Thermal Extremes

The historical and ongoing developments of the regional climate indicate progressive warming, changing trends, and complex weather patterns depicted by near-surface *in-situ* measurements, satellite observations, human perceptions, and climate model simulations[3,12,25]. Hence, subject to regional warming effects, the West African Monsoon (WAM) system creates hotspots of extreme weather events along the coastline, home to densely populated low-lying cities and economic hubs along the arid semi-arid regions[4,5,25]. As a result, there has been a decreasing trend in the number of cool nights and more frequent warm days, warm nights, and heat waves[25]. At the local scale of the Soudan/Sahel subregions, a new pattern of rainfall regime has emerged since the 1990s characterized by a mixture of several pluviometric extremes during single rainy seasons, including false onsets and early cessation of cropping seasons, heavy rain events, and long dry spells[4,5]. Along the Guinean zone, the observed stationarity of the rainfall regime can be attributed to a more intense second rainy season due to the late withdrawal of rains from the coastal regions and to more significant interannual variability of rainfal[26].

The analysis of state-of-the-art climate change scenarios revealed that temperature would continue increasing, the diurnal temperature range (DTR) will keep on reducing (Fig. 1A), with the increase of the average air temperatures (**Supplementary Figure S2a**), an increased frequency of heat extremes such as scorching days, and hot nights[25]. It is well established that high night-time temperatures significantly impact crop production by decreasing photosynthetic function, sugar, and starch content, increasing respiration rate, suppressing floral development, and hastening crop maturity[31]. These findings are consistent with previous assessments based on global and regionally downscaled climate model outputs[69,108,27]. A consensus is also observable on the increase in average rainfall and more extreme weather conditions in the region. The Soudan/Sahel zone may likely experience an average rainfall increase within 10–20% or more, with a spatial dipole in its Western subregions covering Senegal, The Gambia, and Guinea Bissau.

In contrast, the Guinean zone may experience a quasi-stationary rainfall regime (**Supplementary Figure S2b**). This pattern corroborated in previous assessments[28,29] is also observable in the latest simulations of CMIP6 models[27,30]. Daily rainfall events are likely to become more intense but less frequent in combination with longer intra-seasonal dry spells (Fig. 1B), causing other agroclimatic extremes and compound events like false onset and early cessation of the cropping seasons, shorter cropping season, farm inundation, droughts, and heat stress for staple crops (e.g., Millet, maize, sorghum, cowpea, and tubers). Also, floods associated with heavy rain events and large storms (stronger gust winds) will become more common. Moreover, the SSP126 and SSP370 show that agricultural droughts are more frequent without a clear spatial pattern in the 2031-2060- and 2071–2100 time horizons (**Supplementary Figure S3**). This mixed dry/wet pattern of the rainfall regime was attributed to global warming through internal variability of the dynamic factors of the regional atmosphere and the warming of the ocean's surface temperature[31]. At the same time, the dominance of greenhouse gases explains future projections of wetter conditions in the Soudan/Sahel zone[32]. Many other weather-related risks are also associated with temperature extremes, although other climate variables such as rainfall, wind gusts, radiation, and humidity contribute to compounding the challenges.

Needs for Adaptation in Crop, Livestock, and Fishery Production Systems

According to the consensus of scenarios, without adaptation measures, a broad range of changes in cereals yield is reported, with an overall average yield reduction unevenly distributed over a region for grains (e.g., pearl millet, sorghum, maize, and rice), tubers and roost crops, groundnut, cowpea, soybean, and cotton under different rainfall regimes (**Supplementary Figure S4**). From the **Supplementary Figure S4**, pearl millet is less sensitive to warming rates below two degrees among the cereals partly because of its solid coping capacity in adverse conditions. For rice varieties, whose growth cycle is assumed to be invariant over the actual and projected future needs, a slight increase in yield of about +9% could be observed. However, for cases where a shortening of the growing cycle induced by higher temperatures is accounted for, decreases in yield could reach -42% relative to reference periods[33]. Yam production is also expected to decrease by 28% for every 1^{o}C increase in temperature because warming contributes to the proliferation of pests and diseases, affecting yam growth, development, and production[34,35].

Meanwhile, cassava is less negatively impacted by climate change (−3.7% to +17.5%) as it is drought tolerant and not easily damaged by heavy rains[36]. However, floods were found to be detrimental to cassava yields. Thus, there is an inverse relationship between cassava yield and climate parameters with a significant negative effect of increasing maximum temperature. Generally, rising temperatures are less affected by soybeans and groundnuts since the photoperiod limits the crop duration and the CO_2 fertilization effect[37]. Although by the end Century, over 60% of bean growing areas will have to transition towards alternative crops and legumes (e.g., soybean & groundnut), which represent promising agribusiness opportunities under climate change[38]. The future regions suitable for growing crops are relocated to the Soudan-Savanna for groundnut and maize, and millet and sorghum remain applicable across all agro-ecological zones. Cotton production benefits mostly from chemical fertilizers distributed by the national cotton companies and favored by the private sector investments. When integrated soil-crop management and high mineral fertilizer levels are used, future cotton productivity is expected to increase slightly by around +7 to +31% under all future climate change scenarios[39,40]. However, high amounts of rainfall during the germination stage are unfavorable for cottonseeds, and rainfall variations during the maturity stage have a significant adverse effect on yield[40].

Therefore, water availability and the predictability of crucial factors such as onset, length, and cessation of rainy seasons, will be critical for cotton production in West Africa. For cocoa, large parts of production areas will become unsuitable for display in the future and will be converted[41]. This highlights a strong differentiation of climate vulnerability within the cocoa belt, as areas in the Western, Central, and Eastern regions will likely become hotter and wetter[41,42]. The most vulnerable areas are near the forest-savanna transition in Nigeria and eastern Côte d'Ivoire. In contrast, the least vulnerable areas are in southern parts of Ghana, Côte d'Ivoire, and Liberia[42,43]. Interestingly, cashew and shea nut trees may likely be strained by climate change dynamic factors (*e.g.,* increased frequency & intensity of winds, intense rainfall, increase in temperature) and unfavorable diseases[44,45,46].

Livestock will be affected negatively by change through heat stress impacts on animal performance[47], water availability, the quality, pastoral resources[8,48,49], reproductive performance, milk, and meat production[48,50], livestock mobility (i.e., redistribution of grazing spaces and corridors), and animal diseases[49,50]. The length of consecutive heat stress days for dairy cattle, with intensities higher than the severe and dangerous thresholds, is likely to increase (**Supplementary Figure S5**). Under future climate conditions, the average length of periods with extreme and dangerous heat stress is expected to grow from ~3 days in the historical period to ~4–7 days by 2021–2050 and even to up to 10 days by 2071–2100. Around 22% of the dairy cattle population is also expected to experience about 70 days more severe/dangerous heat stress, especially in the southern half of West Africa[50]. Hence, significant decreases in productive and reproductive performances will be within −22% relative to the 1981-2010 baseline. Therefore, the interaction between transhumant herders and host communities intensifies competition over natural resources (*e.g.,* transhumance corridors), triggering conflicts resulting from heat stress and water availability due to climate extremes.

Inland fisheries and aquaculture may also be impacted indirectly by climate change through the depletion of resources in water bodies, the proliferation of parasites and ichthyotoxic plants[19,20,51], inundation, and salinization of land and coastal freshwaters because of Sea Level Rise (SLR), increasing the frequency of floods, storms, and storm surge expected in riparian and coastal zones[51].

Needs for Adaptation in Hydrology and Water Resources Management

Climate change is expected to impact river basins and water supply systems significantly. Floods associated with intense rainfall became more common in the region from the 1990s with significant human security, including damage to production, communication, transport systems, and health and livelihoods[3,12]. Moreover, the projected demographic pressure in West Africa (~2 billion estimated population by 2050) will result in rising demands, posing substantial threats to water security[2], and significantly modifying hydrologic regimes and natural ecosystems. The major rivers in the region presented small changes in discharge at the regional scale, with median results (different time horizons, scenarios, and models considered) within the range of ±5%[52,53,54] (**Supplementary Figure S7**). At the basin scale, except for The Gambia and Senegal river basins, which exhibit a significant negative of 8-16% and 22-26%, respectively[52,55], consistently with the drying pattern projected for precipitation in this subregion (**Fig. 2**). The overall relative change signal over most of the significant basins is unevenly distributed overall relative change signal with both positive and negative values. This opposite tendency was partly attributed to the structural uncertainty of the hydrological models[54] and the reference period used[56]. Other rivers across the region often present non-significant median relative changes in discharge, implying that the impact of climate change is small or not precise, even if it could potentially be strong in some cases (**Fig. 2**). However, at the local scale, the results highlight zonal contrasts in median runoff changes between western (dry) and eastern (wet) of the Sahel and between the North and more robust decreases in discharge) and the southwest (pronounced increases) regions of West Africa (**Supplementary Figure S8**). Most basins are experiencing flood events with magnitudes expected to increase, with alarming extremes due to high sensitivity to climatic and land-use changes, improper dam management[57,58,] and settlements in flood-prone areas[59,60].

Therefore, water sanitation and hygiene (WASH) may be impacted due to many forms of water pollution, such as salinization of groundwater, intrusion of sediments, organic carbon, pathogens, and pesticides which will significantly affect populations[60,61,62]. Groundwater, which contributes in some cases to assuage the threat of climate change on water availability, may highlight a decrease in quality, especially for unconfined shallow aquifers offering little or no attenuation to contaminants coming from the polluted surface under flooded rivers and lagoons. Although simulated changes suggest that the average recharge of groundwater storage in the central Soudan/Sahel zone may increase by the 2050s and in the western coastal regions, significant decreases are predicted[63,64]. However, there is no clear tendency about the impact of climate change on drinking water supply coverage for domestic/municipalities because groundwater contributes in some cases to reduce the threats. Irrigation water needs are projected to increase by 15% to 30% depending on the basins by 2050 as well[64,63].

Decreasing river discharge and increasing evapotranspiration associated with global warming might pose a severe threat to hydropower[65,66,67]. The development infrastructure on river basins often involves trading off competing objectives in an uncertain environment with many transboundary and nexus issues that need to be well-integrated and managed accordingly[67,66].

Potential Impacts on the Coastal Zones

The West African coastal areas, coastlines, and littorals are exposed to changes in ocean parameters such as sea surface warming, sea-level rise, wave heights, ocean deoxygenation, flooding, and erosion[21,68]. In the near-term future, estimates of ocean warming along the coastlines may range between 1.5-2.5°C and 1-3.2°C from the mid to the end of the 21st Century (**Supplementary Figure S9**). From Sierra Leone to Guinea-Bissau, the West Coast is exposed to swell ocean waves from the North and South Atlantic that are low to moderate energy[69]. The future change of annual significant wave heights (Hs) is more important in the Guinean coastal countries in the near term, and a substantial decrease in Hs was projected in a long time. Sea level rise (SLR) represents a threat to West African coastal communities. It is linked to coastal hazards such as storm surges, inundation of low-lying areas, coastal erosion, and damage to coastal infrastructure and ecosystems[70,71].

SLR is the main factor affecting coastal vulnerability, estimated to be moderate-to-very high in some study area[71,72]. Changes in the Ocean chemistry are dominated by ocean acidification, which is oxygen depletion or deoxygenation[21,73]. However, because of significant uncertainties in potential biogeochemical effects and the evolution of tropical ocean dynamics, there is a lack of consensus on the future volume of oxygen-poor waters[74]. Coastal marine ecosystems (e.g., the mangrove) and fishing are affected. They may continue being concerned in the future as increases in Ocean warming and weakening of the upwelling due to unfavorable wind at some locations may lead to serious rippling effects on the productivity of small pelagic fish species region[75,76,77]. Therefore, the maximum catch potential of fish stocks is projected to decline by more than 50% by the 2050s, with the most significant reductions in countries nearest the equator except for countries like Cabo Verde, Gambia, and Senegal[78]. Given the rates of SLR and the predicted future shoreline vulnerability calculations (**Supplementary Figure S9**), the West African mangroves will face the threat of being wholly inundated should sea levels rise beyond levels they can cope with (**Supplementary Note 2**).

Costs of Inaction, early and delayed Actions on Adaptation

Recent reports have been issued providing adaptation costs at global and regional levels, including an analysis of adaptation finance gaps in Sub-Saharan Africa[23]. The highest adaptation costs are projected to be needed in water supply, coastal zone protection, infrastructure, and agriculture sectors[6,23,24]. The practices fitted to and deemed sustainable relative to the future West African climate are scored and ranked according to practitioners' suitability, effectiveness, feasibility, representativeness, and perceptions (**Table 1a & b**). The topmost, high-scoring adaptation options are given in **Fig. 3**, with much better perceptions by the local populations, easy to implement (high feasibility), and having apparent effectiveness and representativeness according to a S.W.O.T-based analysis. As the impacts of climate change may also alter and shift the global cultivation area of various crops, the extent of the water body and coastlines[24], the estimation of costs is, because of this, expressed in the adequate standard unit (e.g., Hectare, Cubic meter, or Kilometer) useful for interpolations on much larger scales (e.g., countrywide, basin-scale, regional, etc.). Estimating adaptation options in agriculture, water resources, and coastal zones are categorized into "costs of inaction" and the costs associated with the implementation, known as the "costs of the action." The latter consists of using the current market costs of similar options are then adjusting them to reflect market prices over time, considering depression, discount rates, interest, and projected inflation rates[79].

Crop production. The climate-related impacts on crop production vary according to crop types, climate change scenarios, and timeline. The costs of action/inaction differ depending on adaptation options. When early measures are deployed in support of crop management, the project cost is expected to reduce shortly after implementation. However, Three categories of crops are investigated, namely cereals (e.g., Rice, Maize, Millet, Sorghum), tubers and root crops (e.g., Yam and cassava), and cash crops (i.e., Peanuts/Cowpea). For crop production, the current implementation of Agroforestry will cost USD514.9 per hectare (/ha), followed by stones bunds (USD509.77/ha), and finally, small-scale adaptation options (USD168.5/ha) (e.g., Zai technics, Mulching, etc.), which are specific to the semi-arid zones. Going the "*Rocky Road*" (i.e., SSP370 scenario), initial inaction costs in crop production are estimated to be USD575.44/ha, and the estimate for the SSP126 method will amount to USD392.78/ha by the 2050s. Crop production losses are higher for tubers & roots crops (e.g., yam) than cash crops (*e.g.,* peanut) and cereals. The cost of inaction on crop production is expected to soar in the nearest future, with a larger uncertainty spectrum found in the SSP370 scenario (**Supplementary Figure S10**). Due to initial investment costs, the action costs appear more elevated than the inaction costs. However, they will become deficient when considering depreciation, representing 13-20% of the initial costs depending on the type of adaptation option (**Fig. 4**).

Livestock and Transhumance. Transhumance is a system of livestock production characterized by regular seasonal movements occurring between complementary ecological zones under the care of a few herders. This breeding method generates conflicts between farmers in host countries and transhumant herders because of the pressure on shared water and natural resources[7,48]. Several policies and legislations have emerged in the different states of the West African region to reduce or prevent farmers-herders conflicts and promote sustainable transhumance. However, the operationalization of these texts is not a reality[47]. The projected climate extreme events will likely accentuate transhumance in the sub-region where some countries such as Benin, the Ivory Coast, Togo, and Ghana have become host or transit countries[7,8,47]. Therefore, in the medium and long term, adaptation options in the livestock sector would require an innovative and applicable legal framework, legislation, and multistakeholder platforms for collaboration and consultation among livestock sector actors/stakeholders (herders, farmers, decision-makers, etc., researchers, practitioners, etc.). Recommendations for an efficient legal framework for the sustainable management of transhumance are available (**Supplementary Table S2**). For sustainable grazing spaces and corridors, goods and services may need only USD18,693.37 to build a reference 250 ha protected reserve. However, proper implementation of the legal framework, monitoring, evaluation, and management system must be undertaken to support rural development, reduce conflicts, and improve the practice of transhumance and raising livestock (**Supplementary Table S2**).

Water Resources and Coastal Zones. The losses and damages in the water resources sector are estimated at USD7.7 per cubic meter. Implementing multi-use reservoirs will cost only USD1.6 per cubic meter. The adoption of rainwater harvesting will cost USD2,852.8 per hectare of crops, while drip irrigation and permeable rock dams will cost USD2,756.0 and USD300.7, respectively. In West African coastal areas, floods often result in considerable material loss and damages (e.g., damage to crops, destruction of houses, bridges, etc.). To prevent injuries or reduce effects, investing in seawalls, breakwaters, revetments, and groins will cost USD5,250,000.0/km, USD3,663,003.0/km USD1,440,000/km, and USD660,000.0/km, respectively. The investment costs were reduced (i.e., USD262,500, USD91,575, USD36,000, and USD26,400 per km, respectively) when considering the depreciation, which corresponds to only 8-11% per annum of the cost of inaction. The estimated cost of inaction will amount to USD3,164,020 per km (**Supplementary Table S1, and Fig. 4**).

With increasingly recurring and projected hydrometeorological hazards, the growing user needs for weather, climate, and environmental services, the capacity standards of the national responsible for early warning, civil protection, and disaster management services must be improved to make countries weather-ready nations[80,81,6]. In 1-5 years, the investment needed was estimated at 3.4-6.9 million US Dollars relative to the situation in 2019/2020 to cover permanent staff training and capacity building, small accessories to improve the working environment (e.g., internet connection, complimentary electricity supply to cover intermittent power, replace or repair computers/hardware), and data and information management networks in West African countries. Further costs of investments were elaborated by the *Hydromet Initiative*[6] (https://www.worldbank.org/en/programs/africa_hydromet_program) to modernize national and regional organizations to improve and sustain the quality of the services gradually. The investment needs were estimated at USD324.5 million (including USD290 million for the member states and USD34.5 million in support of regional institutions) considering available cost estimates from already existing projects in West Africa.

Summary and Ways Forward

Under the increased warming of the regional climate, the number of climatic hazards will continue to grow, including the occurrences of pluviometric extremes such as false onset and early cessation of cropping seasons, longer dry spells mixed with heavy rain events[31]. It is expected that when floods occur because of more intense and frequent heavy rain events[4,5], they are likely to be mixed with agricultural droughts appearing without an apparent spatial coherence. These mixed wet-dry patterns of inland rainy seasons combined with heat waves will negatively impact agriculture and water resources. Meanwhile, the projected oceanic parameters of the Atlantic Ocean (*e.g.,* sea surface warming, ocean acidification, sea-level rise, and increased wave heights) may result in the very high vulnerability of some coastal areas. The impediments of climate change in the coastal regions may include relaxation of upwelling (*i.e.,* reduction of phytoplankton), fishing decline, storm surges, beach erosions, groundwater, and inland salinization.

The operationalization and scaling up of adaptation actions remedy the expected, widespread, adverse effects of climate change into transformative opportunities for the region. The regional landscape analysis shows some evident but informal progress in adaptation practices of local communities to increase the resilience against the ongoing environmental and future climate-related challenges. Several well-fitted adaptation options are identified as technical, management, infrastructure/equipment, and classified for their suitability, potential scales of implementation in agriculture, water sector, and the coastal zones (**Table 1**). To a large extent, technical and management practices can be adopted without external intervention or assistance. They cost little to operationalize and demonstrate strong positive effects on crop production, land, and labor productivity despite consecutive heavy rain events and prolonged dry spells, as revealed by on-farm case studies and pilot projects[8,12,23,82,83]. The infrastructural/equipment measures are likely to require significant capital investment as the case is in the coastal areas where large-scale construction will be needed to overcome SLR, storm surges, floods, erosion, salinization of inland cropping land, and shallow aquifers. Investment costs (action without delay) for infrastructural/equipment measures become lower considering value depreciation and the rate of loss and damages they are meant to avoid. As climate extremes are increasing, any delayed action will strain investment and soar both the financial, human, and material costs as loss and damages may likely increase in agricultural, water resources, and coastal zones. These results are based on field evidence to guide investment, and specific needs for adaption of West African countries, against the current and future climate change potentially full of hydrometeorological hazards, while keeping a green growth pace for all.

However, before many of these adaptation practices can be implemented, short-term measures involving policy development, knowledge transfer, and relevant partnerships and frameworks must first be established. Concerning associations, various actors are already engaged at all scales. These actors, including the private sector, need to work together to complement each other, avoid unnecessary duplications, and foster synergies among climate actions for adaptation. The basis for building more fitted adaptation frameworks in West Africa are co-production, provision of customized, robust, and reliable information, capacity building, and communication strategy adapted to local users. The weak legal framework and legislation of the region and the political instability (including the ongoing security crisis in the Sahelian subregion of Mali, Niger, Burkina Faso, northern Nigeria) create barriers to meeting adaptation needs and cause failures to comply with significant scale climate actions promoting successful implementation of adaptation options[9]. Therefore, policy developments in the region should prioritize integrated water (natural) resources management focusing on the nexus approach[84] and create legal frameworks and legislation for multistakeholder consultation and collaboration platforms among sectoral stakeholders (*e.g.*, herders, farmers, landowners, decision-makers, etc.) to reduce conflicts and alleviate poverty in rural areas. As the adoption and uptake of adaptation options are based primarily on local beliefs and knowledge, it is much fitted to apply soft measures such as gender equity[85,86], climate services[82,83,87], protection insurance schemes[88,87], nature-based solutions embedded with indigenous knowledge[89,90], all supported by research and innovation in adaptation science[91,92]. These non-structural adaptation options can optimize the suitability, effectiveness, and potential scale integration in operational implementation over the region.

Nonetheless, the significant challenges for operational adaptation include i) producing more to feed a rapidly growing population, ii) alleviating the adverse effects of weather and climatic extremes, and iii) reducing the overall contribution to greenhouse gas emissions. However, all the priority adaptation options identified here are clean and aligned with the West African countries' green growth policies and economic emergence goals. Therefore, for closing the gap in their operationalization and upscaling, significant investment efforts should be developed at national and local levels, with funding coming from sovereign wealth funds of countries in the private sector and complemented by concerted responses at the global level.

Data And Methods

1. In-situ and Gridded Observations

Our customized simulation designs were based on observed station data (*in-situ*), including daily rainfall, maximum and minimum temperature, and other variables, provided by the meteorological services and agencies of the West African countries to WASCAL (www.wascal.org) following country-specific data sharing policies[93]. This assessment used *in-situ* data from 132 synoptic stations and 44 discharge stations to calibrate our crop and hydrological models[94,95] and 14 erosion hotspots in coastal zones to compute the coastal vulnerability index (**Supplementary Fig. 1**). The synoptic station data were quality controlled[5,34,] and the 44 daily discharge gauges data were gap-filled[94]. For climate trends and variability analysis, West Africa is divided into three subregions: the Sudan/Sahel zone, the Guinean, and the coastal zones. The West African *Soudan/Sahel* zone is characterized by a long dry season followed by a unique rainy season peaking in July-August-September. The spatial distribution of total annual rainfall decreases northward from ∼1,200 mm to 200 mm, and it is mainly concentrated over a short period of ~ four months. Most rainfed cereals and few tubers are grown in this zone. The natural factors affecting the intra-seasonal variability of the rainfall regime in the Sahel include the local forcing of the Saharan dry air masses, dust, and pollution aerosols[96,31]. The *Guinean* zone is the area of a moist evergreen forest where annual rainfall is between 1500mm and 1800mm and divided into two seasons which alternate with two dry seasons. The natural vegetation is generally grassland and woody transitional forests. The crops are mostly maize, yam, rice, millet, sorghum, groundnuts, and cotton; sugar cane is grown in the wetter parts. Livestock, primarily trypanotolerant cattle, sheep, and goats, are few. This sub-zone includes southeast Guinea, northern Liberia, Cote d'Ivoire, middle Ghana, the middle belt of Nigeria, and southern Cameroon (**Supplementary Figure S1**).

Sea-level Coastal zones include all coastlines, littoral, and shores of the region stretching from the Senegal-Mauritanian upwelling areas down to the south-eastern parts of the Gulf of Guinea. Weather and climate features are mainly embedded within the West African Monsoon (WAM). The regional-scale circulation features of WAM include the latitudinal movement of the intertropical convergence zone (ITCZ), the Saharan heat low (SHL), the variability of lower-to-upper-tropospheric circulation features such as the African Easterly Jet (AEJ), the Tropical Easterly Jet (TEJ), the African easterly waves and other low-level westerly jets. The global oceans also play a significant role in modulating the observed seasonal rainfall and the recent changes in the past climate signal[31,32]. The greenhouse gases are the main factors explaining the future climate patterns of the region[32].

Other observations include gridded mean monthly precipitation (P) and minimum and maximum temperature (Tmin and Tmax, respectively) datasets for the historical period (1981–2010). They were extracted from the WATCH Forcing Data methodology applied to the ERA-Interim data (WFDEI)[97] meteorological forcing dataset at a grid resolution of 0.5°x0.5°. The WFDEI data set merged with the *in-situ* data from synoptic stations to update the baseline status's temperature maps and times series (**Supplementary Figure S2a&b**).

2. Downscaled and Bias-corrected Climate Change Scenarios

We combined various Representative Concentration Pathways (RCPs) scenarios and the Shared Socioeconomic Pathways (i.e., SSP1 based on RCP2.6 named SSP126 and SSP3 based on RCP7.0 named SSP370)[98]. The Global Circulation Models (GCMs) used were downscaled and bias-adjusted in the Inter-Sectoral Impact Model Intercomparison Project (ISIMIP3b, https://www.isimip.org/). The bias-adjustment method is described in Lange [99]. The bias adjustment in ISIMIP3b was the WATCH-ERA5 (W5E5) dataset[100]. The selection of these models was motivated by: (i) structural independence in terms of their ocean and atmosphere model components and (ii) process representation which was reported in an informal survey among experts to be fair (IPSL-CM6A-LR, MPI-ESM1-2-HR) and sound (GFDL-ESM4, MRI-ESM2-0, UKESM1-0-LL). Moreover, the selected GCMs represent the whole CMIP6 ensemble as they include three models with low climate sensitivity (GFDL-ESM4, MPI-ESM1-2-HR, MRI-ESM2-0) and two models with high climate sensitivity (IPSL-CM6A-LR, UKESM1-0-LL). Other datasets are based on Weather and the Research Forecasting (WRF) and the Consortium for *Small-scale MOdelling in CLimate Mode* (CCLM) regional climate models (RCMs). These RCMs were used to downscale the GCMs under RCP 4.5 for the West African region[101,102]. A bias correction has also been performed on the outputs using a multivariate bias correction (MBC) considering the inter-dependency between climate variables in the historical and future periods[103]. The MBC datasets were generated at 0.11x 0.11 degrees horizontal resolution.

Future projections focus on two different combination scenarios representing different shared socio-economic pathways (SSPs) and Representative Concentration Pathways (RCPs). The SSP1-RCP2.6 (SSP126), knowns as "*the Sustainability*" scenario (i.e., Taking the Green Road), describes a world marked by strong international cooperation, prioritizing sustainable development. The underlying assumption of the radiative forcing is based on RCP2.6. It is likely to keep global temperature below 2oC with substantial land-use change (increased international forest cover), low emissions, and 445ppm carbon dioxide (CO_2) by 2100. RCP2.6 requires CO_2 emissions to decline by 2020 and zero by 2100. The SSP3-RCP7.0 (SSP370), known as "*the Regional Rivalry*" (i.e., A Rocky Road), depicts a fragmented world affected by competition between countries, slow economic growth, policies oriented towards security and industrial production, and little concern for the environment. The underlying assumption of radiative forcing is based on RCP7.0 with substantial land-use change (decreased global forest cover), medium-high emissions, and 871 ppm CO2 in 2100. More combinations of SSP/RCP scenarios that provide narratives describing alternative socio-economic developments can be found in Meinshausen et al. [98]. While SSP126 represents the low end of the range of plausible future pathways, SSP370 represents the medium-to-high end of future emissions and warming[98]. For climate change signals and impacts assessments, the 1981–2010 period was considered as the reference "*Baseline,"* and two horizons were defined for the future, namely 2031–2060 (Horizon 1) and 2071–2100 (Horizon 2). Where observed data time series is not a constrain, the assessments are conducted seamlessly over 1979–2014 (to cover the most recent historical period of observations) and 2015–2100 for the future projections under SSP126 and SSP370.

3. Impact Assessments

Crop model simulation design

CERES and CROPGRO, embedded in the Decision Support System for Agrotechnology Transfer version 4.7 (DSSAT4.7, www.dssat.net)[105], and interfaced with R software (DSSAT-R)[106], were used to undertake spatial yield simulations for millet, maize, rice, and cotton productions under a changing climate. The climate forcing data files (WTH.LST) were extracted from historical (*In-situ* & models' outputs) datasets and projected SSP126 & SSP370. The Soil input data was extracted and formatted from ISRIC (Global Soil Information Based on Automated Mapping[107,108], and HC27 (Global high-resolution soil profile database for crop modeling applications) generic soil profiles, soil hydraulic properties derived from pedo-transfer functions[108,] and soil physical and chemical properties required by the crop models.

The cropping areas considered for each crop were digitized and portrayed in **Supplementary Figure S5**. Some regional crop management practices were also deemed to be based on field for rainfed regimes and applied over all grid points of the climate model. The millet, maize, and cotton were planted at 5 to 7 cm depth in a 100 × 100 cm row spacing with 2 to 3 plants.m^{-2} was observed at emergence. The planting dates were identified as "the first day between April 1 and July 31 when at least 40% soil moisture in the top 20 cm depth is reached. The minimum temperature does not drop below 11°C for millet cultivars " the maximum temperature does not exceed 35°C. Organic matter estimated at 500 kg

ha^{-1} of crop residues is added. Different improved hybrid rice cultivars (i.e., IR8 and TOX 3107) adapted to West Africa rainfed conditions were planted, with 50–100 $plants.m^{-2}$ as planting density observed at emergence. The planting date was the first day between May 1 and June 30 when at least 50% soil moisture in the top 20 cm depth is reached, the minimum temperature does not drop below 20°C for rice cultivars, and the maximum temperature does not exceed 35°C. Mineral fertilizers were applied in NPK 15-15-15 at seedling at 100 $kg.ha^{-1}$ and Urea at 50 $kilograms.ha^{-1}$ at the 20 and 40 days after sowing. The output of all the simulations was analyzed considering the relative percent difference between the average yield and biomass production of rainfed millet and rice. The changes for the horizons 2031–2060 and 2071–2100 were estimated relative to the baseline 1981–2010.

Hydrological modeling and coastal vulnerability simulation designs

Two hydrological models, GR4J and IHACRES[109,110,] are used to investigate the impacts of climate change on streamflow over seven major transboundary river basins (i.e., The Comoe, Gambia, Mono, Niger, Oueme, Senegal, and Volta basins) covering more than 90% of the West African region (Fig. 3 and **Supplementary Figure S6**). Both models are lumped conceptual models, computationally attractive (due to few calibration parameters), and convenient for data-scarce environments. To assess the performance of these two models, the baseline period is subdivided into two subperiods representing overall dry (1981–1995) and relatively wet (1996–2010) conditions. To ensure the robustness of the simulations, models are calibrated and validated on both wet and dry periods (**Supplementary Note 1**). The ability of models to represent hydrological regimes is assessed through the Kling Gupta Efficiency (KGE) criterion[111]

The potential coastal vulnerability was treated by calculating the coastal vulnerability index (*CVI*)[112]. The basic physical-geological parameters used include sea-level rise, geomorphology, coastal slope, regional elevation, shoreline change, significant wave height, and tidal range taken from ISMI2b and ISIMIP3b datasets. Wave energy is related to capacity for erosion, where relief and vertical land movements are considered indicators of inundation risk.

The CVI is described as the square root of the product of these physical-geological divided by the number of variables (n).

$$CVI = \sqrt{\frac{a * b * c * d * e * f}{n}}$$

2

a: Geomorphology; b: shoreline change rates; c: Coastal slope/relief; d: Relative Sea-level rate; e: Significant wave height (Hs); f: Tidal range. Factors *a* and *b* are obtained from the literature, *c*, *d*, and *f* are derived from satellite data, while *e* is obtained from outputs computed by the WAVEWATCH III model (https://github.com/noaa-emc/ww3) forced by the wind from global models. Three of the six variables will change to calculate the CVI for the future. These variables are Hs, the sea level rise rate, and the shoreline erosion/accretion rate. The CVI values obtained are divided into four classes with percentile ranges as 0–25%, 25–50%, 50–75%, and 75–100%. The upper quarter will be taken as "*very high vulnerability,"* the lower quarter will correspond to "*low vulnerability*," and the remaining two classes will represent in ascending order "*moderate*" and "*high vulnerability."*. The results of this investigation are exposed in (**Supplementary Note 2**).

4. Analyses of Costs of Action and Inaction

The data processed in this paper emanated from several coproduction fora and surveys (e.g., series of workshops, focus group discussions and experts' interviews, high-level meetings with stakeholders, and the administration of individual questionnaires to agropastoralists, farmers, households, and other users of climate services) designed to develop adaptation tools for West Africa, mainly conducted between January 2018 and April 2020. The data are complemented by an in-depth literature review of the peer review papers and country reports; a lot of grey literature was used, in the form of consultancy reports, Ph.D. theses, conference proceedings, symposium/workshop reports, project reports, book chapters, and publicly available web sources.

Estimating the costs of adaptation tools involves several ramifications and complexities. In this assessment, we based our reasoning on the assumption that climate change is a "*global good*" with long-term influence, uncertainty, volatility, and some level of ambiguity. The costs of the adaptation options correspond to the investment costs of implementation and other external costs (where applicable), and the benefits are the damages, return on investment, and social benefits that the strategy is expected to avoid (i.e., crops and income losses, co-benefits from the implementation of adaptation options). An analogical method has quantified the costs associated with these damages, known as the "*costs of inaction*," and the expenses related to implementing the identified adaptation options, known as the "*costs of the action."* The Cost-benefit analysis was conducted in two stages, whereby identified adaption options are clustered based on a numerical SWOT analysis according to their representativeness, effectiveness, feasibility, and household perceptions. The S.W.O.T (Strength-Weakness-Opportunity-Threats) analysis was built upon a 5-point rating scale with 0 being "very poor" and four being "very good" for "Strengths" and "Opportunities." For "Weaknesses" and "Threats," the scale is negative and twisted, with − 4 being "high level of Threats and Weaknesses" and 0 being "no threats and Weaknesses." In each case, the SWOT scores are cumulated to identify the level of Representativeness, Effectiveness, Feasibility, and perception level, with 8 being the highest score and 0 being the lowest. Therefore, the topmost, high-scoring adaptation options, with much better perceptions by the local populations, are easy to implement (high feasibility) and have apparent effectiveness and representativeness for agriculture and water resources and coastal zones (Fig. 3 and Table 1a**&b**).

After completing the S.W.O.T-based clustering, these topmost, sustainable adaptation options are valued from the angles of costs of action, inaction, and investments. The latter consists of using the average market prices over the 2010–2019 period for similar options in the ECOWAS countries of West Africa.

Then the costs are adjusted to reflect price trends over the period 2021–2060 while considering depreciation, discount rates, and projected inflation rates.

Estimates cover the following costs for each identified adaptation option: large equipment, small equipment, professional labor, and non-professional labor. When the costs of an alternative have been estimated in the past, the present value of these costs is considered. Therefore, we have capitalized these values using the inflation rate in the ECOWAS zone as provided by the International Monetary Fund (IMF) (https://www.imf.org/external/datamapper/PCPIPCH@WEO/OEMDC/ADVEC/WEOWORLD).

Hence, if C_n is the cost of an adaptation option, to establish the capitalization value C_t, we add up all the flows generated by the investment as:

$$C_t = C_n \times (1 + i)^{t-n}$$

1

Where:

C_n is the value of the flow in year n

C_t is the value of the flow in the previous year (year t)

i is the annual interest rate for risk-free investments

$t - n$ is the number of years between the flow payment (year n) and the previous year.

As the impacts of climate change may also alter and shift the global cultivation area of various crops[24], the extent of the water body and the coastlines, the estimation of adaption costs are at this moment expressed in the smallest relevant standard unit (*e.g.*, Hectare, Cubic meter, or Kilometer). The estimated expenses cover small equipment, large equipment, and professional and non-professional labor.

Declarations

Data availability

- The ISIMIP3b data are available for download from https://www.isimip.org/
- The bias-corrected WASCAL High-resolution climate simulation datasets can be downloaded free from the WASCAL Data Infrastructure (WADI) at https://wascal-dataportal.org/2.0/
- The raw, uncorrected WASCAL high-resolution simulation outputs can be downloaded at https://cera-www.dkrz.de/
- Crop, hydrological, coastal vulnerability index simulations outputs, and economic estimation data are available upon request through the corresponding.

- The inflation rates for the 15 countries of the Economic Commission of West African States (ECOWAS) are available at https://www.imf.org/external/datamapper/PCPIPCH@WEO/OEMDC/ADVEC/WEOWORLD.

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Author contributions

S.S. designed the study. S.S, S.S, M.S, K.H, M.D.B. E.K.D, I.C, M.D.B.D, K.H, B.M.T. created customized simulations and data analyses. M.S & B.M.T performed the hydrological model and water resources simulations, S.S performed the cos-benefit simulations, S.S., E.K.D, K.H, M.D.B.D, K.H, performed the crop-climate model simulations, I.C & M.D.B.D performed coastal vulnerability simulations. M.D.B.D performed the bias-corrected high-resolution simulations. S.S conceived the paper. All authors contributed to writing, proofreading, and commenting on the manuscript.

Competing interests.

The authors have no competing interests as defined by Nature Research, or other interests that might be perceived to influence the interpretation of the article.

Materials & Correspondence.

The *in-situ* climate datasets, customized DSSAT-R scripts for the agroclimatic simulations, and the R scripts used to determine the agro-hydro-climatic parameters are all available upon request to S. Salack (salack.s@wascal.org). The hydrological lumped models are open access. The parametrized versions for the major river basins of West and Central Africa are also available upon request to M. Sidibé (moussa.sidibe01@gmail.com) and S. Salack (salack.s@wascal.org). The outputs on the coastal vulnerability index are available upon request to I. Camara. The excel spreadsheets of cost-benefit simulations are available upon request to S. Sanfo (sanfo.s@wascal.org) and S. Salack (salack.s@wascal.org).

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Results

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Tables

Table 1a | List of adaptation practices in crops and water resources management

Adaptation practice	Scale*	Category**	Suitability
Stone Bunds	S/M	I	Relevant for subregions with projected increase in extreme rainfall events (e.g., Central & Eastern Soudan/Sahel)
Halfmoon	S/M	T	Particularly relevant for degraded lands with projected water stress (e.g., Western Soudan/Sahel)
Zai	S/M	T	
Sand Dune Stabilization	S/M	T	The increasing speed at which desertification is progressing in Sahelian countries makes this technology one of the main instruments for combating the impacts of climate change. Suitable mostly in the semi-arid subregions of West Africa
Permeable Rock Dams	S/M	I	Relevant for regions with a projected increase in extreme rainfall events (e.g., Eastern Sahel). Serve the double purpose of prevention against erosion and provision of additional cultivated areas.
Conservation Tillage	S/M	T	Land conservation and restoration techniques suitable mostly in the Sahel and Sudan regions
Grass Strips	S/M	T	
Changing Cropping Calendar	L	M	Particularly relevant across West Africa, where models predict erratic rainfall with high interannual variability in agriculturally relevant rainfall characteristics (e.g. extreme rain events, wet/dry and hot spells)
Short Duration Crop	L	M	
Crop Diversification & Intercropping	L	M	Ensures more resilient planting system Particularly relevant in the context of global warming and projected changes in West Africa
Post-harvest Storage	L	T/M	Relevant across West Africa to ensure food security and adapt to off-season erratic rainfall
Agroforestry	L	T	Tolerant to climate variability based upon the tolerances of the perennial species
Assisted Natural Regeneration	S/M	T	Particularly relevant for degraded lands. Mostly the Sahelian band in West Africa
Mulching	S/M	T	Reduces water loss, suppresses weeds, reduces raindrop splash effect, reduces soil temperatures, and generally improves crop productivity through the gradual addition of soil nutrients. Suitable for land restoration and efficient water usage. Relevant for the entire West African domain under global warming
Improved Fallows	S/M	T	
Use of	L	T	Particularly relevant for degraded land with poor soils.

Organic Fertilizers			Represent a greener alternative to inorganic fertilizers.
Integrated Nutrient Management	L	M	Requires significant number of animals exhaust, as cattle dung is useful in making compost and micro dose of chemical fertilizers. More relevant on marginal Sahel lands. Runoff needs to be controlled so that the compost/manure added to the soil is not lost. Combined with other practices such as stone bunds, halfmoon, and permeable rock dams.
Rainwater Harvesting	L	E	Relevant for the entire West African region considering projected high intra-seasonal variability (e.g., Heavy rains events mixed with long dry spells)
Irrigation (Drip Irrigation)	L	E	Water efficient irrigation techniques, suitable for predicted high water stress regions in full irrigation (off-season) and supplementary irrigation (on-season)
Multi-purpose Reservoirs	L	I	Particularly relevant for transboundary and NEXUS issues. Well Fitted into improve food production, hydropower generation, irrigation needs, and water sanitation and hygiene, supply for domestic/municipalities and the general physical and social infrastructure in rural areas
Livestock Grazing Space	L	T	Source of domestic animal feeds, it addresses transhumance needs and agropastoral conflicts. Applicable at all the regional scale and countries
Mixed Crop-Livestock Farming	L	T/M	Provides a source of nutrient and financial security to rural populations. Relevant at the regional scale
Pest Management	S/M	M	Particularly relevant across West Africa under global warming conditions as changes in key climate variables might induce outbreak of pests and livestock diseases

***Scale:** S = small, M = Medium, L= Large; ** **Category**: T= Technical, M = Management, I = Infrastructure/Equipment

Table 1b | Same as **Table 1a** for the coastal zones

Adaptation practice	Scale*	Category**	Suitability
Storm Surge Barriers	S	I	Relevant for protection against storm surge occurrences. Might be implement at specific locations due to the high maintenance costs
Cliff Stabilization	S/M	T	Coastal management practice to be considered for application over a long stretch of coastline. Particularly relevant for countries such as Mauritania and Ghana
Flood Mapping/Risk Assessment	L/M	T	Important process to be undertaken at the scale of West Africa to ensure preparedness. Combined solutions including raising structures above floodplains and identifying properties at risk
Flood Proofing and Sheltering	L	M	
Drought Warning System	L	T	Particularly relevant across West Africa to provide critical information to alleviate food insecurity, water resources depletion, conflicts over natural resources, loss of life (animal and human) under climate variability and change
Construction of Dikes	S/M	I	Particularly relevant for low-lying flood-prone areas. Important option to consider across West Africa, particularly in countries where extreme wave conditions are projected
Construction of Seawalls	S/M	I	Relevant for countering coastal flooding or recession and erosion. Particularly relevant at the regional scale with projected increases in Sea Level Rise
Construction of Jetties	S	I	Suitable for intercepting sediments transported alongshore. Could be implemented to mitigate channel siltation
Construction of Groynes	L	I	Most popular method used across West Africa to mitigate coastal erosion
Construction of Breakwaters		I	Mostly implemented at harbours to reduce wave actions on ships
Revetments of dikes/Seawalls	S/M	T	Provide supplementary protection to existing defences such are dikes or seawall
Beach Nourishment	S	T	Often adopted as a temporary solution. Very expensive option in the long-term which might be relevant only for extreme cases

*__Scale:__ S = small, M = Medium, L= Large; ** **Category**: T= Technical, M = Management, I = Infrastructure/Equipment

Figures

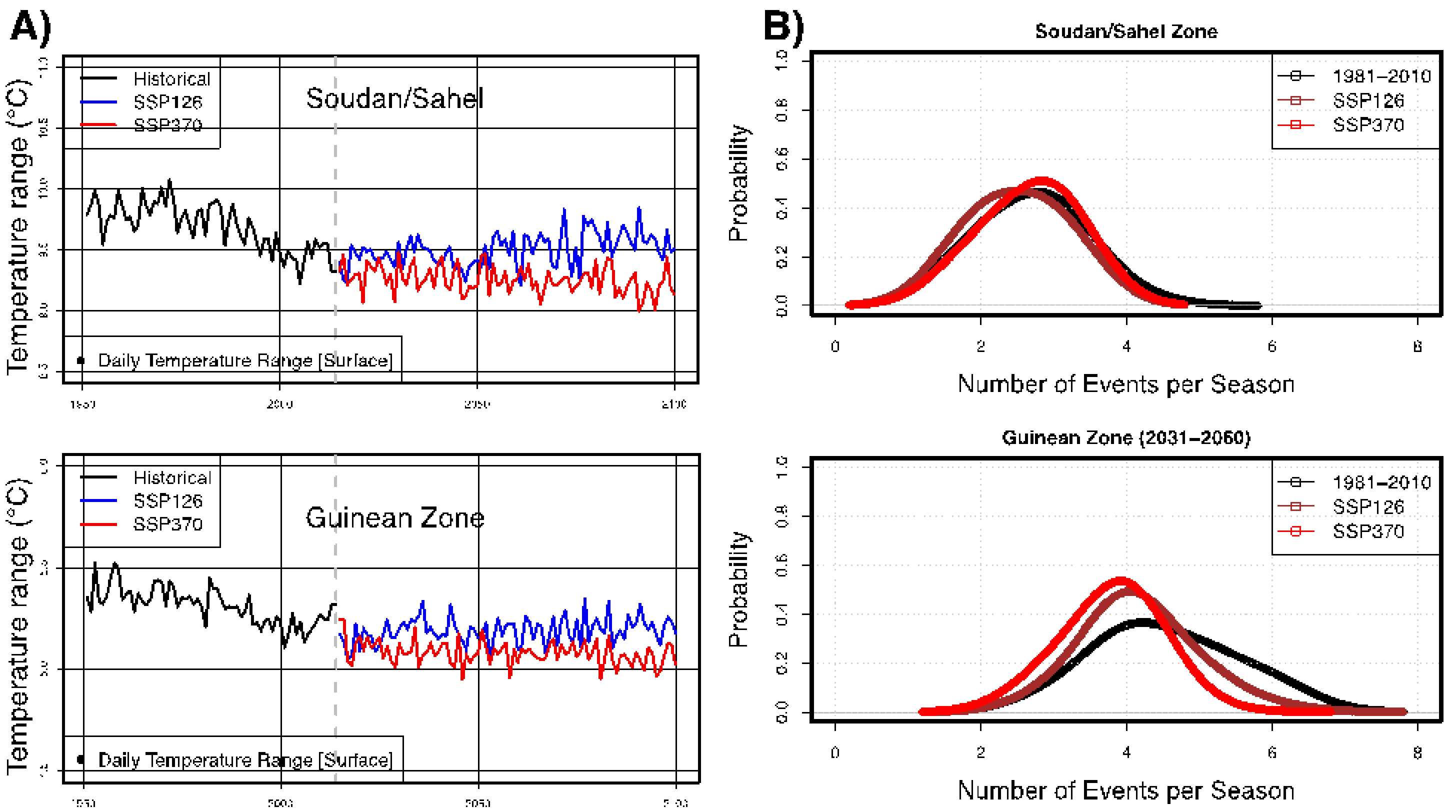

Figure 1

A) Interannual variability and trends of the near-surface area-averaged daily temperature range (DTR) depicted over the Soudan/Sahel and Guinean zones of West Africa. The series 1950-2014 are based on observations combining *in-situ* and gridded data. The projected 2015-2100 are derived from shared socio-economic pathways SSP126 & SSP370 scenario using five bias-corrected and downscaled global circulation models from the intersectoral impact model intercomparison project (ISIMIP3b). B) Average seasonal distribution of heavy rain events (HRE) during the 2031-2060 horizon over the West African climatic zones.

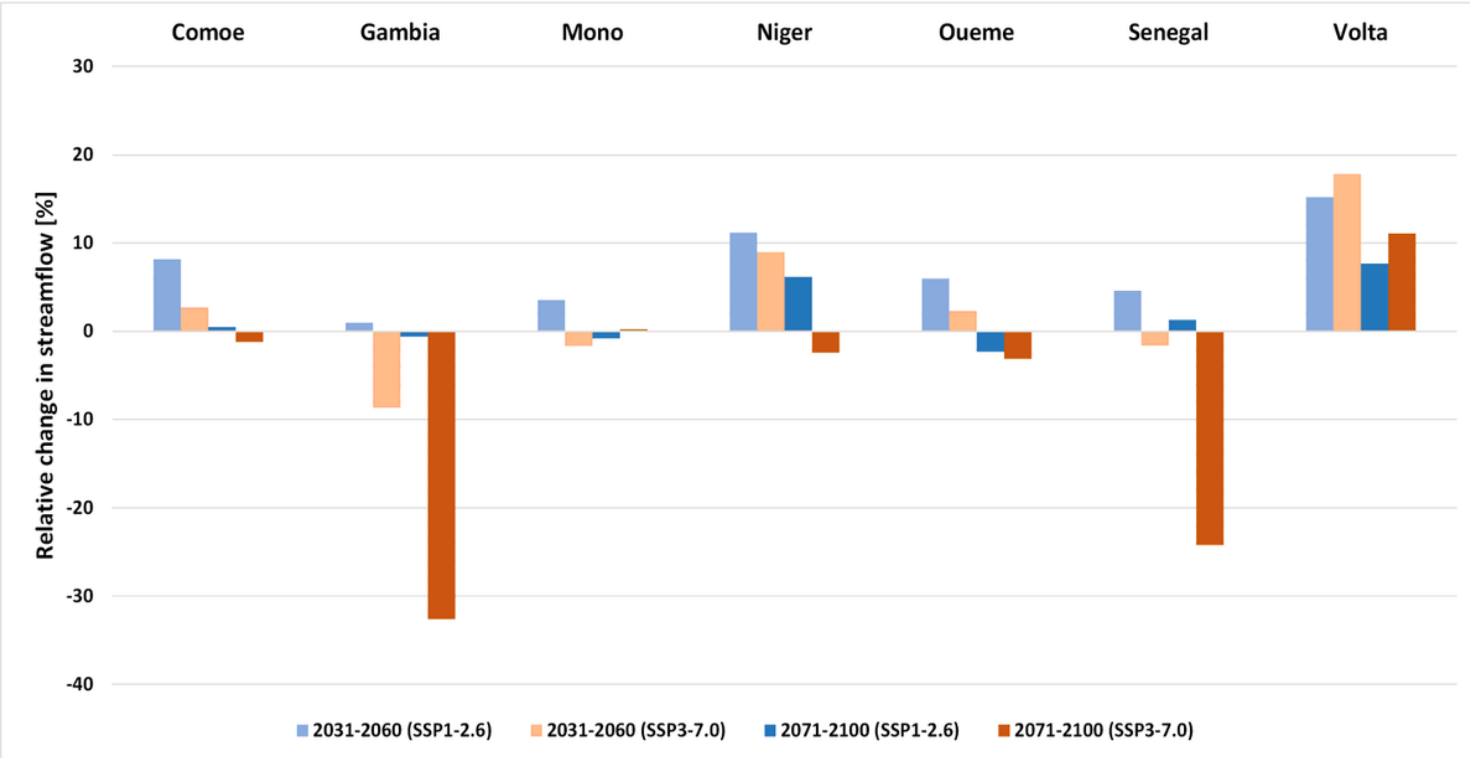

Figure 2

Changes in streamflow (%) relative to the 1981-2010 baseline for seven major river basins in West Africa.

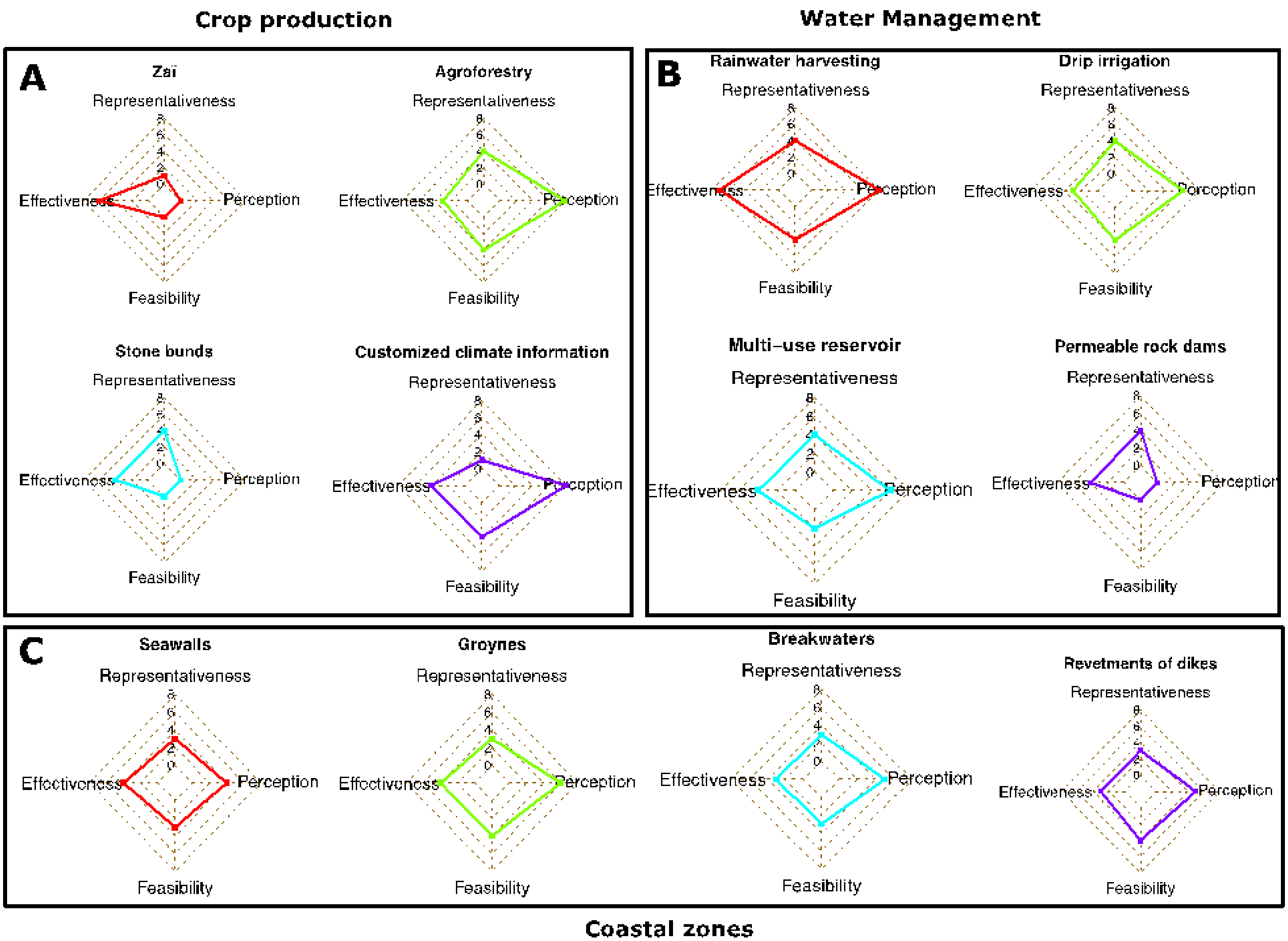

Figure 3

High scoring adaption options and measures suitable for crop production and soil water conservation (**A**), water resources management (**B**), and the protection of the coastal zones (**C**) of West Africa under climate extremes.

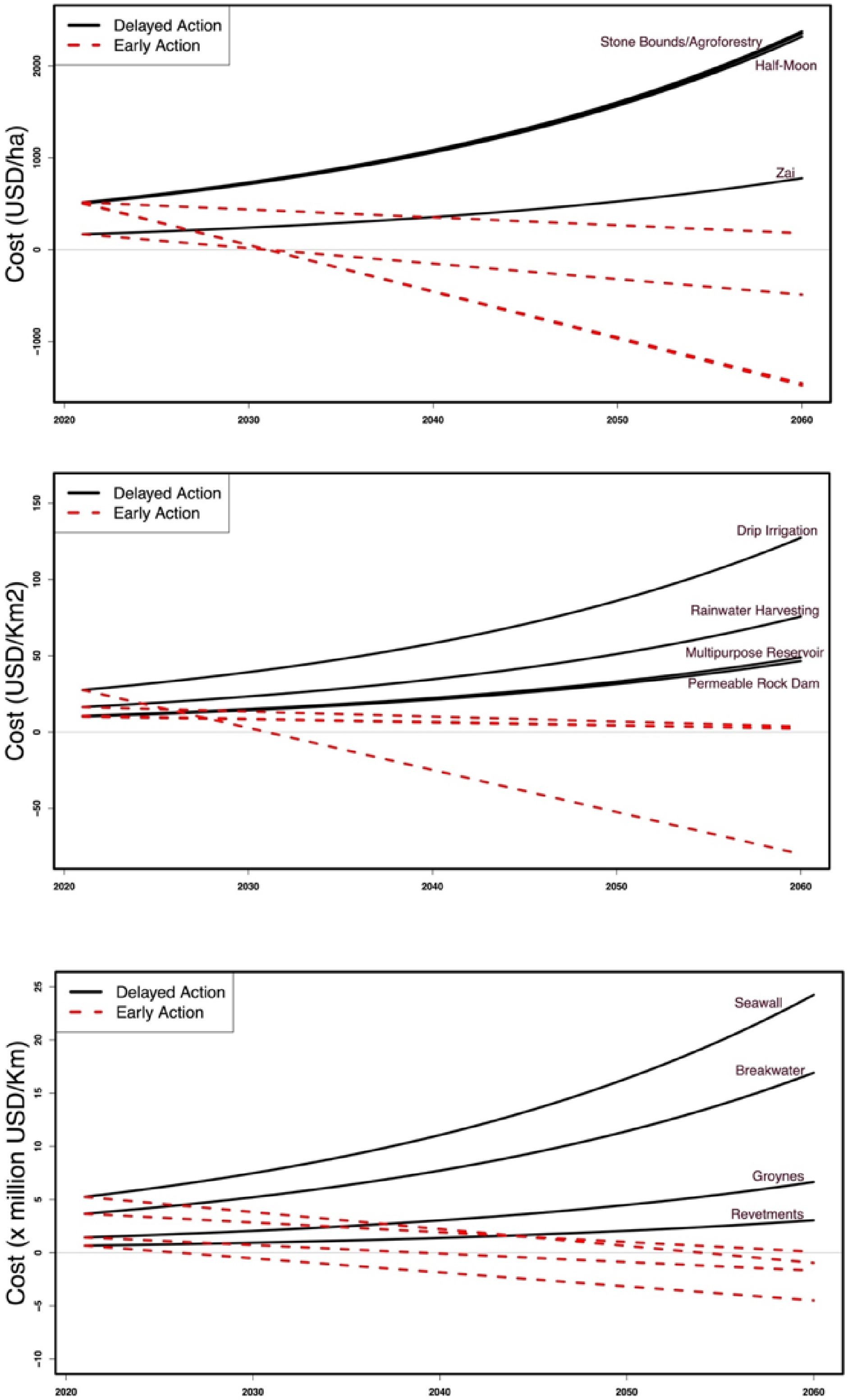

Figure 4

Projected costs of delayed (early with depreciation) implementation of adaptation measures when applied to crop management, water management, and the protection of coastal areas.

Supplementary Files

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