Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development

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Abstract

Development efforts for poverty reduction and food security in sub-Saharan Africa will have to consider future climate change impacts. Large uncertainties in climate change impact assessments do not necessarily complicate, but can inform development strategies. The design of development strategies will need to consider the likelihood, strength, and interaction of climate change impacts across biosphere properties. We here explore the spread of climate change impact projections and develop a composite impact measure to identify hotspots of climate change impacts, addressing likelihood and strength of impacts. Overlapping impacts in different biosphere properties (e.g. flooding, yields) will not only claim additional capacity to respond, but will also narrow the options to respond and develop. Regions with severest projected climate change impacts often coincide with regions of high population density and poverty rates. Science and policy need to propose ways of preparing these areas for development under climate change impacts.

Keywords: adaptation, climate change, development, impacts, modeling, sub-Saharan Africa

Introduction: Africa's development challenge under climate change

Africa has the largest share in poor and undernourished people (Kates & Dasgupta, 2007; Fao, 2010) and is projected to have the largest population growth rates (Lutz & Samir, 2010) as well as above-average climate change (Christensen *et al*., 2007) over the 21st century. Recently, there has been strong economic development in several African countries, most notably e.g. Angola, Chad, and Equatorial Guinea, (World Bank, 2011) and this development is likely to continue but under increasing pressure from a growing population and under climate change. Climate change affects ecosystem functioning and the provision of ecosystem services and is thus of considerable concern to human societies and economic development. In consequence, climate change impacts have been the subject of ample scientific publications, which mainly analyze the consequences of unmitigated climate change and the prospects of adapting to climate change. However, there is little information available on possible effects of climate change for socioeconomic development in Africa (Hope, 2009; Conway, 2011; Lemos *et al*., 2012).

There is a variety of studies addressing impacts of climate change on various biosphere properties, e.g. on freshwater availability (Arnell, 2004), biome shifts and ecosystem dynamics (Scholze *et al*., 2006; Heyder *et al*., 2011), or agricultural production (Müller *et al*., 2011; Müller, 2013). Scholze *et al*. (2006) and Heyder *et al*. (2011) have thoroughly assessed climate change impacts on natural ecosystems, addressing ecosystem stability and functioning and analyzing the role of uncertainty in climate change projections for their impact assessments. Their metrics focus on system stability (ratio of change to variability) (Heyder *et al*., 2011) or impact likelihood of change (Scholze *et al*., 2006). Many studies, however, use a limited selection of climate scenarios, that often seem to be selected at random [see e.g. studies reviewed by Müller *et al*. (2011)], and employ different metrics of change, which renders these assessments difficult to synthesize. Consequently, climate change impacts are often addressed for singular aspects only, although the ability to deal with climate change impacts can be greatly reduced if multiple stresses are present simultaneously (Quinn *et al*., 2011). The limited use of several emission and climate scenarios in many impact studies also prevents analyzing the role of uncertainty in climate change impact assessments, a central point for decision making. Only recently, different climate change impacts have been analyzed in combination, highlighting the possible interaction of climate change impacts (Fraser *et al*., 2013; Elliott *et al*., 2014; Piontek *et al*., 2014). Within the intersectoral impact model intercomparison project (www.isi-mip.org), Piontek *et al*. (2014) have analyzed global hotspots

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of climate change, identifying regions in which several impact sectors (surface freshwater availability, crop productivity, ecosystem change, malaria) overlap spatially. While Piontek *et al.* (2014) are able to account for the uncertainty embedded in the impact models of each sector by employing a multitude of impact models per sector, we here address a broader set of climate model realizations. We also employ a single impact model framework, so that impact projections for the different biosphere properties are not only consistent with respect to driving climate data, but also with respect to modeling detail and process interaction.

Both current livelihood strategies as well as possible future development options can be impacted by climate change. African societies will need to develop under climate change and adapt to climate change simultaneously. Their ability to address these challenges depends on many social aspects (Smit & Pilifosova, 2003), which vary greatly across sub-Saharan Africa. Also, the heterogeneous exposure to climate change impacts needs to be considered in development and adaptation strategies.

We here present a composite measure of the severity of climate change impacts on the biosphere in sub-Saharan Africa. We focus on biosphere properties relevant to African societies: flooding probability, dry periods, total surface freshwater availability, water requirements for cropland irrigation, ecosystem productivity, and crop yields (see Table 1, Figure S1 in Appendix S2), which we simulated with the process-based impact model LPJmL (Sitch *et al.*, 2003; Bondeau *et al.*, 2007; Biemans *et al.*, 2009, 2011; Waha *et al.*, 2012; Schaphoff *et al.*, 2013) driven by a broad range of climate scenarios. The likelihood of impacts, their mean strength, and the high-end scenario provide complimentary information for policy and decision makers and we discuss implications for adaptation and development strategies.

Materials and methods

Climate data

To analyze a broad range of climate change projections, we use 40 different climate scenarios; 19 for the SRES A2 scenario, and 21 for the SRES B1 scenario (Table S1 in Appendix S1). Climate data were obtained from the Coupled Model Intercomparison Project phase 3 (CMIP3) multimodel data set, supplied by the Program for Climate Model Diagnosis and Intercomparison (PCMDI) and the World Climate Research Programme's (WCRP's) Working Group on Coupled Modeling (WGCM). All data were interpolated from the original GCM resolution to a regular 0.5 degree grid using bilinear interpolation. As raw GCM data are often affected by a biased representation of today's climate that can lead to spurious simulation results, a bias correction based on observed climate data was performed for monthly mean temperatures, monthly precipitation, monthly cloudiness, and wet day frequency, see Supporting information for details.

The dynamic global vegetation, hydrology, and agriculture model LPJmL

The process-based ecosystem model LPJmL simulates natural vegetation at the level of biomes composed of nine plant functional types (PFT) (Sitch *et al.*, 2003) and agricultural land, distinguishing 12 representative crops and managed grassland (Bondeau *et al.*, 2007; Lapola *et al.*, 2009; Müller & Robertson, 2014). The simulation of carbon and water fluxes and pools (Schaphoff *et al.*, 2013) explicitly accounts for the dynamics of natural and agricultural vegetation. All processes are modeled at a daily resolution and on a global 0.5*0.5°grid, except for carbon allocation and competition of natural vegetation, which are simulated at annual time steps. The suitability of the model for studies of carbon and water fluxes, natural vegetation patterns, and agriculture has been demonstrated before by validating simulated carbon fluxes and greening (Lucht *et al.*, 2002), phenology and yields (Bondeau *et al.*, 2007; Fader *et al.*, 2010), river discharge (Gerten *et al.*, 2004; Biemans *et al.*, 2009), soil moisture (Wagner *et al.*, 2003), evapotranspiration (Sitch *et al.*, 2003; Gerten *et al.*, 2004), and irrigation water requirements (Rost *et al.*, 2008a).

The model is not initialized, but vegetation patterns, carbon, and water pools are brought into a dynamic equilibrium with two spinup simulations. For the spinup simulations, the climate data from 1901–1930 are repeatedly used as the best proxy available for preindustrial climate conditions. The first 1000-year spinup simulation with natural vegetation only brings the model into a quasi prehistoric state without human influences. In a second spinup of 390 years, which starts out with quasi prehistoric vegetation, water, and carbon patterns of the first spinup, land-use information is supplied from 1700 onwards (Fader *et al.*, 2010), to take into account the long-term effects of historic land-use change on soil carbon pools. After completion of the spinup, the individual climate scenarios were used as input to generate model outputs for the 80 different scenarios analyzed here (19 SRES-A2, 20 SRES-B1 scenarios), each simulated with two different CO_2 settings: (i) static atmospheric CO_2 concentrations of 370ppm after 2000 and (ii) with dynamic annual CO_2 increases according to the SRES scenarios. By 2100, atmospheric CO_2 concentrations reach 856ppm in the A2 and 549ppm in the B1 scenario. Each climate scenario had its own spinup simulation, because the climate data bias correction chosen (see supporting information) leads to small GCM-specific differences in the historic climate data.

For this analysis, we simulated annual net primary production (NPP) as a measure of ecosystem performance, monthly river discharge as an indicator of surface freshwater availability and the risk of seasonal droughts or inundation, annual irrigation water requirements as an indicator of difficulties in crop management, and crop yields as an indicator of agricultural productivity. We constrain our analysis of

Table 1 Biosphere properties considered, computation summary, and interpretation

Climate Change Impact	Damaging direction of change	Interpretation	Computation
Total surface freshwater availability (annual discharge)	Decrease	Decreasing annual discharge indicates decreasing overall fresh water availability for households, industry, and agriculture (Falkenmark *et al.*, 1989; Arnell, 2004)	30-year mean of annual discharge rates
Flooding probability (Q10)	Increase	Increasing levels of high discharge rates (Q10) indicate higher probability of flooding and damage to infrastructure, as the hydrological infrastructure is less likely to prevent damage at higher discharge peaks.	The high discharge rate is monthly discharge level that is exceeded in only 10% of a 30-year time series
Dry periods (hydrological drought index)	Increase	Increase in hydrological drought index indicates more intense or longer dry periods. This limits drinking water supplies, sanitation, agricultural production, and any facilities that rely on reliable water supply, e.g. for cooling or processing	Number of months below a month- and location-specific minimum threshold (20th percentile of each month's discharge distribution in the reference period) or increase in consecutive dry month of a 30-year time series. For details see Huntjens *et al.* (2012).
Irrigation water requirement	Increase	Increasing irrigation water demand indicates increased risk of mismanagement due to mismatching water supply and demand as well as higher costs of irrigation where infrastructure is available	30-year mean of annual irrigation water requirements, based on distribution of irrigated cropland in about the year 2000 (Portmann *et al.*, 2010)
Ecosystem productivity (NPP)	Decrease	Decreasing NPP indicates reduced vegetation performance, degradation of ecosystems, and reduced ecosystem services (Costanza *et al.*, 1998, 2007)	30-year mean of annual NPP
Crop yield	Decrease	Decreasing crop yields indicate increased risk of food insecurity, poverty, and malnutrition	30-year mean of annual, energy-weighted total cropland production

changes in irrigation water requirements to current irrigated areas, because larger expansions of irrigated areas are complicated by unsuitable socioeconomic conditions in many countries (Neumann *et al.*, 2011) and are often related to the land-grabbing phenomenon, which is difficult to project (Cotula *et al.*, 2011). Water discharge was computed as described by Rost *et al.* (2008b). To assess the different functionalities of water discharge, we computed changes in three different water-related biosphere properties: total annual discharge, high-flow, and hydrological drought. Total annual discharge represents surface freshwater availability is often used as an indicator for water stress (Falkenmark *et al.*, 1989; Arnell, 2004). High flow is measured as Q10, i.e. the monthly discharge rate that is exceeded in only 10% of monthly discharge rates of a 30-year period. Increasing Q10 values indicate increased risk of flooding. The hydrological drought index measures whether monthly discharge falls below the 20th percentile of each month's discharge distribution in the reference period or if the length of consecutive dry months is prolonged (Van Huijgevoort *et al.*, 2012). Increasing hydrological drought index values indicate increased risk of subannual dry periods, in which surface freshwater availability may be constraining. The hydrological drought index is advantageous over a simple percentile approach (e.g. Q90), which would have reference values of zero in most semiarid regions and would thus constrain the analysis to mainly moist areas, where dry periods are of less concern than in semiarid regions. The lack of coherency between flood and drought measures is also founded in the underlying motivation of the two measures. High flow (Q10) is used as a first-order assessment of changes in the risk of flooding and thus needs to consider maximum amounts of discharge, while dry periods, in which access to freshwater may be constraining, need to consider both the low flow amounts as well as the duration of dry periods. The ability of LPJmL to compute seasonal river discharge is described and evaluated by Biemans *et al.* (2009).

All indicators are computed for the land-use pattern of the year 2000, according to the MIRCA2000 land-use data set (Portmann *et al.*, 2010), as modified by Fader *et al.* (2010), but as sugar cane is now simulated explicitly, the areas cultivated with sugar cane are no longer included in the group 'others', but are explicitly located. Future land-use change is not accounted for, thus land-use patterns are assumed static after the year 2000. Changes in crop yields are computed for the 11 crops described by Bondeau *et al.* (2007) and sugar cane as described by Lapola *et al.* (2009) and are presented as the change in each grid cell's total crop calorie production (Table 2). For this aggregation, crop management intensity has been calibrated to match reported yields (Faostat Data, 2009) as described by Fader *et al.* (2010). Crop types considered and their energetic contents [energy per fresh matter based on FAO (Fao, 2001), dry matter content based on Wirsenius (2000)] and the models capability of reproducing national average yields in Africa were demonstrated by Waha *et al.* (2013).

Internal computation of sowing dates was recently revised by Waha *et al.* (2012) to better account for temperature and precipitation seasonalities. Crop sowing dates change with changing climate, assuming that farmers adjust to changing climate conditions (Waha *et al.*, 2012). Varieties are computed as described by Bondeau *et al.* (2007), but variety-dependent phenological heat units (PHU) for spring wheat, rapeseed and sunflower, and base temperature for maize are now dependent on mean annual temperatures (Müller & Robertson, 2014). Crop root biomass allocation is now modified by water stress (Waha *et al.*, 2013), which replaces the modification of the harvest index under water stress as described by Bondeau *et al.* (2007).

Impact measures

We here aim at impact measures that allow for identifying regions with high exposure to negative climate change impacts (hotspots) as well as for ranking regions according to their impact severity for individual as well as across different biosphere properties. We thus only consider climate change impacts to the worse, i.e. changes to the better are ignored here. That is, because averaging over opposite signs typically blurs the occurrence of changes (in the extreme case, conditions change drastically, but opposite signs cancel out). Clearly, these measures cannot be interpreted as balanced aggregate measures of climate change impacts, but are tools for a specific purpose (identification of most severely affected regions). We assume a risk-adverse perspective and are thus interested in the impact strength of negative impacts, while the likelihood of negative impacts occurring is reflected by the multiscenario agreement. Changes are only considered if future projections are significantly different from the reference period (1991–2000) at the 5% significance level according to the Welch's *t*-test. For each climate and (CO_2) scenario (80 scenarios in total), we computed climate change impacts for six biosphere properties (Table 1). Accounting for local and interregional importance, we here consider relative changes in percent as well as absolute changes as also proposed by Heyder *et al.* (2011). While relative changes are prone to excessively emphasize regions with low reference values (typically marginal regions like the Sahara-Sahel border region), they accurately reflect the local importance of changes (small absolute changes may be severe if there is little to start with). Absolute changes, on the contrary, reflect the regional importance of impacts. From a regional perspective, where goods can be traded, changes in the most productive locations may be of largest concern as it strongly affects regional production, even though the relative local change rates may be comparably low. Absolute changes are normalized by the maximum change per biosphere property, if positive changes are considered damaging (flooding, dry periods, irrigation requirements); relative changes are capped at 100%, which happens only in regions with very low reference values. Changes are generally reported as a linear combination of relative and normalized changes, δ [see Eqn (1)].

$$\delta_i = \frac{(p_{i,f}/p_{i,r} - 1) + (p_{i,f} - p_{i,r})/\max(p_f - p_r)}{2} * 100 \qquad (1)$$

where p denotes the biosphere property and the indices indicate the pixel i, the future period f, and the reference period r.

The multiscenario agreement (MSA) is the number of scenarios that leads to a significant change (5% level, Welch's *t*-test) in the damaging direction (see Table 1) and ranges between 0 and 80 for individual biosphere properties and between 0 and 480 for all six. For the individual biosphere properties, the high-end impact (HEI) is the 5% quantile of all 80 scenarios. When all six biosphere properties are analyzed jointly, we define the HEI of the most strongly impacted property as the overall HEI. The median impact (MI) is the median of the changes to the worse of all scenarios (again, 80 for individual biosphere properties and 480 for all six jointly). For HEI and MI, only those biosphere properties were considered that have a reference value (1981–2010) different from zero (Figure S1 in Appendix S2), considering only changes to the worse. The sign of changes was inverted for those biosphere properties for which increases are considered damaging

Table 2 LPJmL crop types used in this study and their energy content

Representative crop type	Crop group represented	Energy content [MJ kg^{-1} DM] (Wirsenius, 2000; Fao, 2001)
Wheat (spring/winter)	Temperate cereals	15.88
Rice	Rice	13.47
Maize	Maize	16.93
Millet	Tropical cereals	16.17
Field peas	Pulses	15.85
Sugar beet	Temperate roots and tubers	12.20
Cassava	Tropical roots and tubers	13.03
Sunflower	Oilcrop sunflower	13.86
Soybean	Soybean	15.40
Groundnut	Oilcrop groundnut	18.42
Rapeseed (spring/winter)	Oilcrop rapeseed	22.47
Sugar cane	Sugar cane	4.65

(flooding, dry periods, irrigation requirements, Table 1) to facilitate comparability between biosphere properties. We here consider 40 different climate scenarios of two GHG emission scenarios, which is a large subset but by no means comprehensive. All impact measures here thus do not reflect the general likelihood (MSA) or median (MI), but only as represented in this subset of climate scenarios.

The climate change impact severity is then a linear combination of MSA, HEI, and MI, all normalized by their maxima [see Eqn (2)].

$$\text{severity}_{i,p} = \frac{\text{MSA}_{i,p}/\max(\text{MSA}_P) + \text{MI}_{i,p}/\max(MI_p) + \text{HEI}_{i,p}/\max(\text{HEI}_p)}{3} * 100 \quad (2)$$

The severity measure thus equally reflects the likelihood of negative impacts to occur (MSA), their impact strength (MI), as well as an indication of possible serious impacts (HEI). We use this severity measure of all six biosphere properties considered here, to identify hotspots of climate change impacts in sub-Saharan Africa. Hotspots are identified for each biosphere property *p*, as well as in combination for all six, i.e. of 480 different cases (80 scenarios for six biosphere properties).

Results

Climate change impact projections

Projected climate change can negatively affect all six biosphere properties considered here but with varying degrees of uncertainty, strengths, and spatial patterns. Here, 'negatively affected' means that living conditions will become less favorable, e.g. through increased flooding probability or reduced crop yields. The spatial patterns show that all of sub-Saharan Africa runs some risk of being negatively impacted by climate change (Fig. 1). In the main text, we focus on the 2080s, representing the end of the 21st century (2070–2099). Information on earlier periods (2010s and 2040s) can be found in the supporting information. As climate change is spatially heterogeneous and there are large differences between GCMs with respect to the spatial patterns of changes, the likelihood of negative impacts in the set of scenarios analyzed is less than 25% in many regions (Fig. 1 a, b). This does not imply that all other scenarios agree on changes to the better (see agreement on changes to the better in Figure S2 in Appendix S2), because changes are only considered if they are significantly different from the reference period. Especially surface freshwater availability, risk of flooding as well as ecosystem productivity and crop yields in marginal areas (panels a, b, e, and f in Fig. 1 and in Figure S2 in Appendix S2), have high interannual variability and projected changes are thus often not statistically significant. The mediating effects of CO_2 fertilization, which is considered in 50% of the scenarios, also lead to lower likelihood of negative impacts on irrigation requirements, ecosystem productivity, and crop yields (Fig. 1 d, e, f, Figures S3–S5 in Appendix S2), but has little effect on total surface freshwater availability, flooding probability, and dry periods (Figures S6–S8 in Appendix S2). Even though median impacts of all scenarios with significant changes to the worse are often moderate (Fig. 2), there is a chance that climate change impacts might be severe, that is the high-end impact is projected to be extreme in various regions, but not in all (Figs 3, 4b). Except for the largely uninhabited desert areas, most regions are at risk of being negatively impacted in several biosphere properties simultaneously (Figs 1 and 4).

In most of sub-Saharan Africa, climate change reduces total surface freshwater availability in 25–30 of the 80 scenarios, with lower probabilities in parts of East Africa and higher probability in the Okavango basin and in southwest South Africa (Fig. 1a). Reductions in water availability are strongest in arid regions, where small absolute reductions can be large in relative terms and thus detrimental to the local population, and in the large river basins, where relative reductions are small, but the absolute reduction in water availability is of concern for a larger region (Fig. 2a). In these regions, impacts can be substantial in the high-end scenarios with both local (e.g. in the southern Sahel) and regional relevance (e.g. in the larger river basins; Fig. 3a). Overall, climate change impacts on surface freshwater availability are most prominent in the (semi)arid regions of the Sahel and southern Africa as well as several larger river basins (Figs 1a and 3a).

For better planning, this general indicator of water availability needs to be supplemented by measures of its variability. Increases in flooding probability are generally moderately likely in sub-Saharan Africa with occurrence in typically less than 25% of the scenarios, but much higher in East Africa (Tanzania, Uganda, and southern Ethiopia), where most climate scenarios project increasing rainfalls (Fig. 1b). Parts of the Sahel, East Africa, and some large rivers (Niger, Congo, Nile, see Fig. 1b) are the most relevant regions in sub-Saharan Africa with respect to increased flooding probability under climate change as they rank high in likelihood, median impact, and high-end impact (Figure S9b in Appendix S2).

Southern Africa, West Africa, and parts of East Africa (Eritrea, Sudan, and Ethiopia) are most likely to be

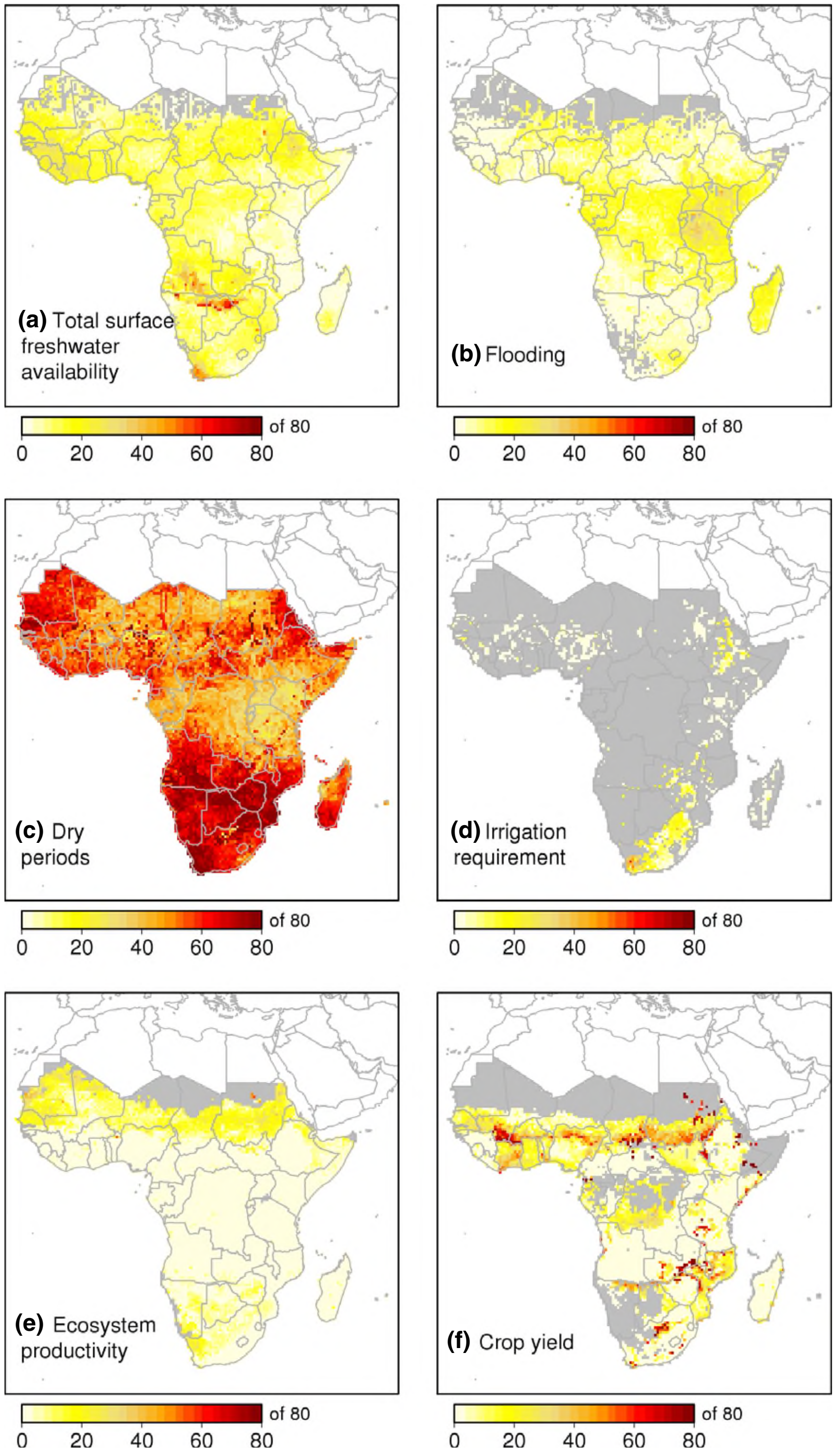

Fig. 1 Multiscenario agreement (MSA) on changes to the worse in the 2080s for (a) total surface freshwater availability, (b) flooding probability, (c) occurrence of dry periods, (d) irrigation water requirements on currently irrigated areas, (e) ecosystem productivity and (f) crop yields. Agreement reflects the number of scenarios of a total of 80 (19 SRES A2; 21 SRES B1, see Table S1 in Appendix S1, each with two assumptions on effectiveness of CO_2 fertilization). Areas with reference values of zero are masked in gray.

affected (Fig. 1c), but likelihood of increasing dry periods is generally higher than for any other biosphere property in sub-Saharan Africa.

Only small fractions of cropland are irrigated in sub-Saharan Africa and these areas are likely to see increasing irrigation water requirements in southern Africa

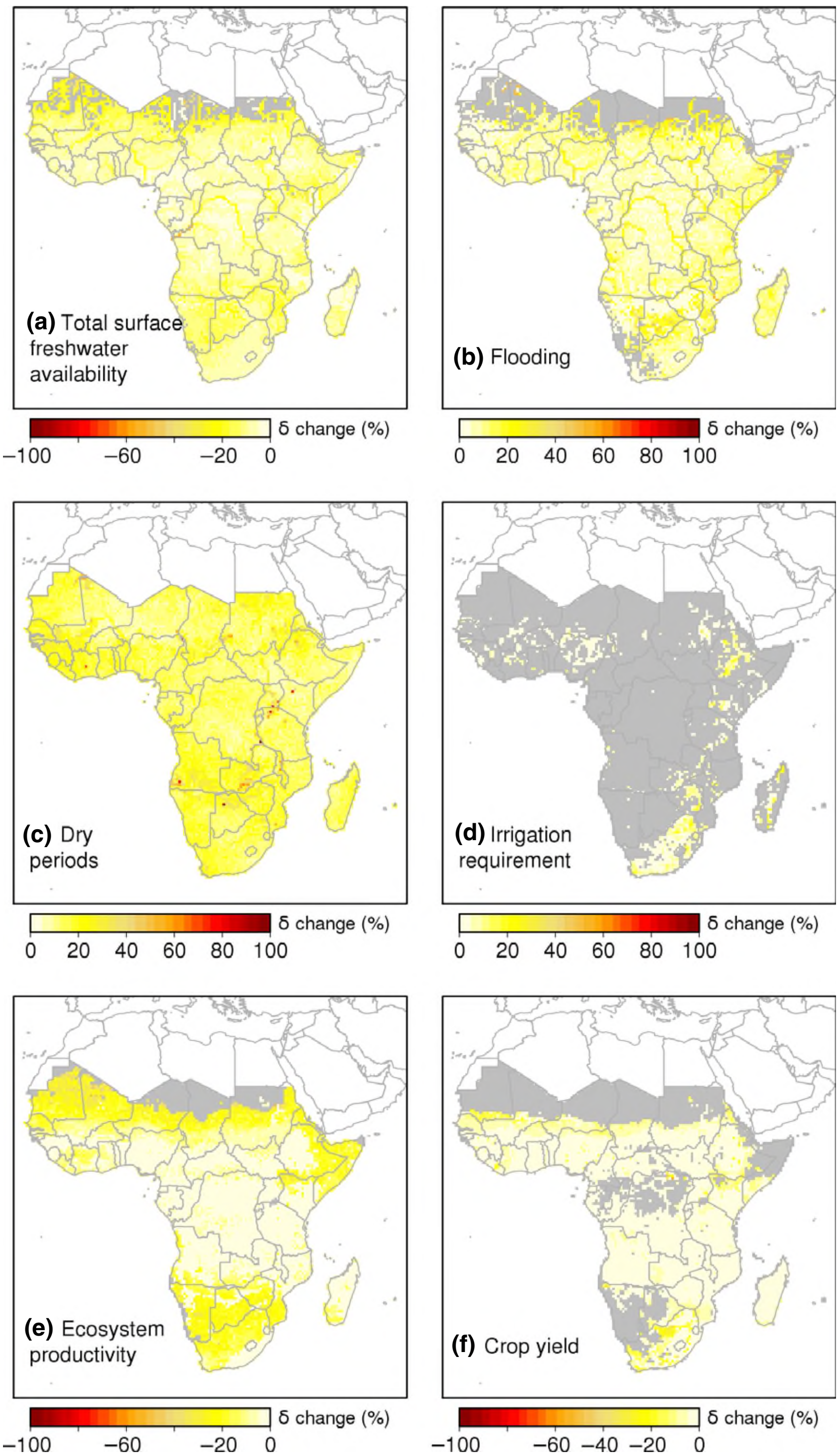

Fig. 2 Median change in biosphere properties in the 2080s for scenarios that project a change to the worse for (a) total surface freshwater availability, (b) flooding probability, (c) occurrence of dry periods, (d) irrigation water requirements on currently irrigated areas, (e) ecosystem productivity and (f) crop yields. The measure δ is a composite of absolute and relative change rates to reflect the importance of large relative changes for the local population and of large absolute changes for the region (see methods).

and the northeast (Ethiopia and Eritrea, Fig. 1d). Impacts on irrigation water demand are largely determined by changes in rainfall, while CO_2 fertilization, which also increases the water-use efficiency of plants (Leakey *et al.*, 2009), shows moderate amplifying effects (Figure S3 in Appendix S2).

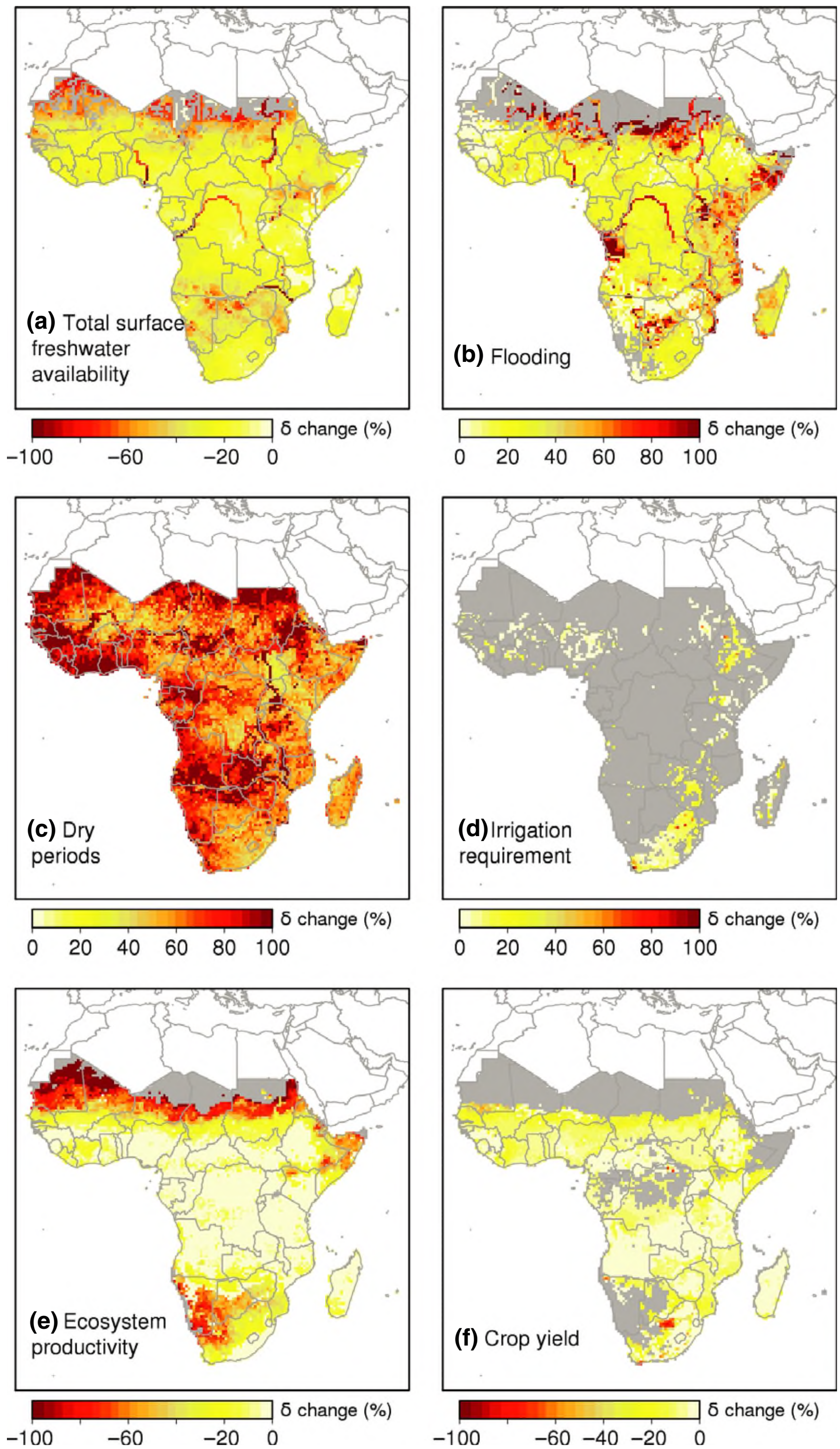

Fig. 3 High-end impact in biosphere properties in the 2080s for (a) total surface freshwater availability, (b) flooding probability, (c) occurrence of dry periods, (d) irrigation water requirements on currently irrigated areas, (e) ecosystem productivity and (f) crop yields. The measure δ is a composite of absolute and relative change rates to reflect the importance of large relative changes for the local population and of large absolute changes for the region (see methods).

Projected climate change leads to declining ecosystem productivity (NPP) only in arid to semiarid regions of sub-Saharan Africa, while the more productive parts show very little likelihood of negative climate change impacts (Fig. 1e), also largely irrespective of the effectiveness of CO_2 fertilization (Figure S4 in Appendix S2).

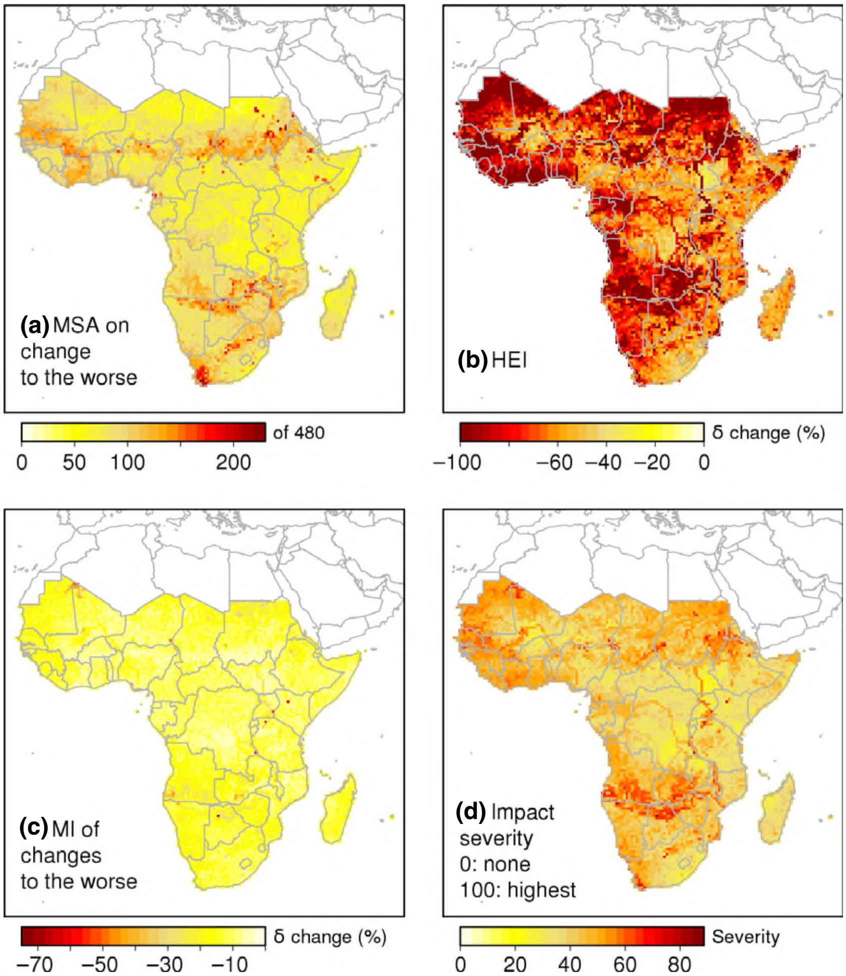

Fig. 4 Hotspots of climate change in the 2080s. Panel (a) displays the multiscenario agreement of negative impacts to occur (MSA); panel (b) displays the high-end impact (HEI); panel (c) displays the median impact (MI) of all scenarios that lead to changes to the worse; and panel (d) displays the severity of climate change impacts. Impact severity of 0 indicates that there is no indication on changes to the worse in any scenario, a value of 100 would indicate that this pixel ranks highest in all three measures (MSA, HEI, MI) for each of the six biosphere properties. For the computation of these measures, see methods.

Climate change impacts drive changes in crop yields across Africa, but are typically more severe and more likely if CO_2 fertilization is assumed to be ineffective (Figure S5 in Appendix S2).

Hotspots of climate change impacts

In many parts of sub-Saharan Africa, several biosphere properties are at risk of being negatively affected by climate change simultaneously and several regions rank high in all three impact traits: likelihood, mean impact, and high-end impact. From a biophysical perspective, these regions are hotspots of climate change as these are the regions where negative impacts are most likely, strong, and possibly severe – and where overlapping impacts may constrain and complicate response options. Parts of West Africa including the western Sahel, the eastern Sahel, the region around Lake Victoria, and parts of the large rivers, Congo, Niger, Nile, Okavango, and Zambezi are hotspots of climate change impacts (Fig. 4). These hotspot regions are characterized by a combination of relatively high likelihoods of negative impacts in all biosphere properties, the possibility of extreme impacts, and that negative impacts are strong on average.

The climate change hotspots in the large river catchments of Congo, Niger, Nile, and Zambezi are determined by water-related climate change impacts, but are generally less susceptible to changes in natural and agricultural ecosystem productivity. High population density and poverty rates in Malawi, Mozambique, Zambia, Zimbabwe, and in the Lake Victoria region render these regions as climate change hotspots of high relevance for adaptation planning.

Discussion

Patterns, uncertainties, and implications

Some regions of sub-Saharan Africa will experience negative impacts of climate change with high certainty, where there is very high agreement among scenarios that conditions will become worse by the end of the 21st century (Fig. 1). These include increases in dry periods in most areas except East Africa, declining crop yields in various parts of the subcontinent, or reductions in surface freshwater availability in the Okavango basin. The risk of increased flooding probability is of particular concern in areas that are subject to severe flooding already today, such as Tanzania (Kijazi & Reason, 2009) and in regions, where increased flooding probability is less likely but could be severe (Fig. 3b). Floods are a general threat to dwellings, agricultural land, infrastructure, and other investments. Temporary dry periods on the other hand can be of equally great importance for drinking water, sanitation, agricultural production, and any facilities that rely on reliable water supply, e.g. for cooling or processing. Development strategies thus need to not only consider total freshwater amounts, but also its seasonal distribution.

While impacts with high likelihood can and must be addressed with specific and adequate response measures, more uncertain climate change impacts require incorporation of this uncertainty into the design of development strategies. As such, the likelihood that various water-related properties of the biosphere will be negatively affected in large parts of sub-Saharan Africa (Fig. 1a–d), clearly calls for improved water management strategies and possibly related infrastructure (*in situ* rain water harvesting, protection against floods and erosion, expansion of water storage capacities, water distribution plans, and treaties etc.) and institutions (Huntjens *et al.*, 2012) there.

The diversity in impacts on crop yields reflects not only the spatial heterogeneity of projected climate change, but also the differences in susceptibility to climate change across crop types and also cropping periods, which are not always assessed well by the LPJmL model in Africa (Waha *et al.*, 2012). Decreasing crop yields may indicate lower income for farmers and reduced food security, but changes in other biosphere properties cannot be linked as clearly to people's welfare. Ecosystem productivity for example may determine people's ability to collect firewood, raise roaming animals, hunt, or gather fruits and can also serve as a proxy for productivity levels of possible future agricultural systems. As such, a decline in ecosystem productivity must be of concern for development strategies. Ecosystem services also strongly contribute to the 'GDP of the poor', i.e. to the livelihood of the poor population and many provisioning and regulating services decline with ecosystem productivity (Costanza *et al.*, 1998, 2007).

Similarly, adaptation and development strategies need to account for possible climate change impacts, even in regions with high uncertainties. These may call for diversification of income, flexibility in production methods, and better market integration, which have been traditional targets of development policies (Duncan, 1998). Such measures, which aim at low vulnerability, become even more urgent in areas where there is some risk of severe climate change impacts (Figs 3, 4b). Climate change impacts, even though uncertain, can be best addressed by measures that yield benefits even in absence of climate change (no regret), that are flexible enough to respond to changes, e.g. by investments with short lifetimes, and/or safety margins that account for uncertainty if these are available at low cost (Hallegatte, 2009).

Overlapping climate change impacts on different biosphere properties do not only reduce people's capacity to respond (Quinn *et al.*, 2011), but also constrain or offer response options. There is some potential that several of the negative impacts on the biosphere can be reduced by suitable adaptation measures (Verchot *et al.*, 2007; Ebi *et al.*, 2011; Huntjens *et al.*, 2012; Notenbaert *et al.*, 2012; Waha *et al.*, 2013). In our simulations, we assume static systems except for adjustments of cropping periods (Waha *et al.*, 2012) which we assume to be implemented by farmers without additional investment or support. If agricultural systems are to be developed into more productive systems with extended irrigated areas, possible future water constraints should be considered (Elliott *et al.*, 2014). Dry periods are likely to increase throughout sub-Saharan Africa (Fig. 1c), which implies that irrigation could at least prolong the cropping period in semiarid regions and rain water harvesting could do so if irrigation water is not sufficiently available (Mortimore, 2010; Ebi *et al.*, 2011). In some regions (e.g. parts of South Africa, Angola, northern Mozambique; Nigeria to South Sudan), water storage options may be explored, as dry periods are likely to increase, while there is only low likelihood of declining total water availability.

Even though the high-ranking parts of West Africa, the eastern Sahel, the region around Lake Victoria, and parts of the large rivers, Congo, Niger, Nile, Okavango, and Zambezi are hotspots of climate change impacts (Fig. 4) with similar severity indication, the driving factors differ between these hotspot regions. The Sahel is a hotspot region because of its susceptibility to negative climate change impacts on total water availability and its variability (risk of flooding, seasonal water shortages), as well as on ecosystem productivity and crop yields. Changes in irrigation water requirements are of minor importance, as irrigated areas are basically absent there. While the western Sahel (northern Mali and Mauritania) is only sparsely settled (Ciesin *et al.*, 2000), there are many more people and also many more poor people (less than 2US$ per day) (Fukuda-Parr *et al.*, 2004) in the Sudan and Ethiopia who are directly affected by these climate change impacts (Fig. 5). Consequently, these regions are not only hotspot regions from a biophysical perspective, but also from a socio-economic perspective.

Methodological caveats

We show that climate change impact projections provide important information for development and adaptation strategies, especially if also addressing uncertainties and possibly overlapping impacts on different biosphere properties. The impact measures employed here are relative measures, i.e. they only serve to compare different regions in sub-Saharan Africa, but they account for the local and regional relevance of changes. There is no theoretical framework for quantification of hotspot regions or the selection of criteria for identifying these. We here quantify three different aspects of impact measures (likelihood, mean impact, high-end impact) which we all consider relevant for adaptation planning and development strategies, but that may have to be supplemented by additional measures for specific purposes. The linear combination of these measures is only meant to identify regions which are likely to be severely affected by climate change impacts, relative to other regions in sub-Saharan Africa. A multiplicative combination of the individual measures leads to very similar patterns, but the variability of values is strongly reduced, hampering the identification of hotspots. We thus decided to use the additive combination. The hotspots of climate change impacts as identified here do not account for mediating impacts from positive climate change impacts, which are not considered here. The results presented here therefore should not be interpreted as a balanced representation of average climate change effects on African biosphere properties, but as an instrument for identifying severely affected regions only.

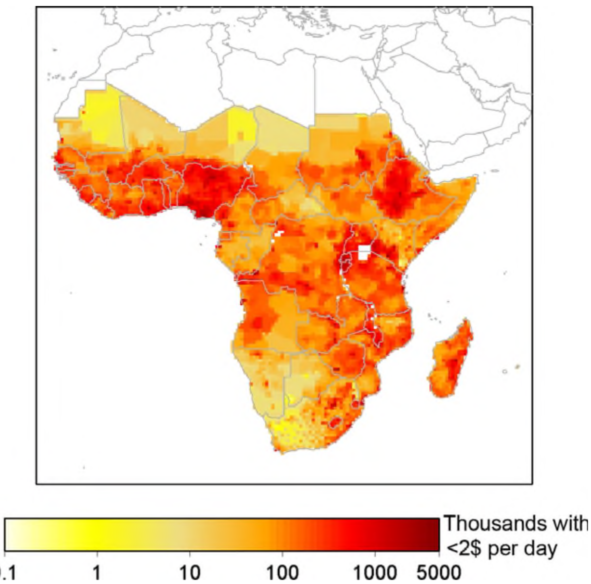

Fig. 5 Distribution of poor population (less than 2US$ per day) in sub-Saharan Africa. Figure based on a combination of gridded population data (Ciesin *et al.*, 2000) and national percentage of poor from worldmapper.org, based on Fukuda-Parr *et al.* (2004). Note that the actual distribution of the poor within countries is likely less homogeneous than assumed here.

The translation of biophysical impacts into implications for people's livelihoods and development options is complicated by the lack of spatially explicit data on the importance of individual biosphere properties for people's livelihoods. We here assume that all biosphere properties are equally important (equally weighted). The comparison of biophysical impact patterns with patterns of population density and poverty (Fig. 5) is an attempt to facilitate such translation from biophysics to socioeconomics, even though poverty is not necessarily an indicator of low adaptive capacity (Mortimore, 2010). Other attempts to map vulnerability in sub-Saharan Africa employ various indicators that can be localized to some extent (Liu *et al.*, 2008; Thornton *et al.*, 2008), but their relationship to the climate change impacts on biosphere properties as discussed here is often not clear and requires considering local specifics on vulnerabilities of the different social groups to the different climate change impacts and their combinations (Preston *et al.*, 2012). Also, the quantitative measures used here are by no means the only possible way to quantify the uncertainty of climate change impacts or their interaction across biosphere properties.

Given these limitations, the implications of climate change impacts for development and adaptation are of general nature as they discuss generally valid mechanisms that require interpretation with local knowledge. We thus also only extensively discuss the changes in the late 21st century, acknowledging that patterns of climate change impacts are not necessarily static in time (Figs. S9, S10, S11 in Appendix S2) or between emission scenarios (Figures S3–S8 in Appendix S2). We also assume static land-use patterns, acknowledging that land-use change affects hydrological processes and could affect changes in water availability, risk of flooding and dry periods (Gerten *et al.*, 2008).

Conclusions

Projections of climate change impacts are subject to considerable uncertainties, combining uncertainties from emission scenarios, climate models, downscaling and bias correction, and impact models (Roudier *et al*., 2011). We use a broad range of climate projections for two different emission scenarios (SRES A2 and B1) (Nakicenovic & Swart, 2000) and multiple general circulation models (GCMs, 19 for A2, 21 for B1, see Table S1 in Appendix S1) to address the uncertainty in climate change projections (Hawkins & Sutton, 2009, 2011). This does not represent the full range of possible future climate scenarios, but comprises a good part of the plausible range. We use only one bias correction and downscaling method (see supporting information) and only one impact model, so that the uncertainty from impact models, which can be substantial (Piontek *et al*., 2014), is not covered here. However, we analyze climate change impacts in one consistent modeling framework with direct interaction between biosphere properties, allowing for a more direct comparison of impacts in different biosphere properties. Expanding on the work of Piontek *et al*. (2014), we also address the uncertainty in the effectiveness of so-called CO_2 fertilization, which is subject to complex interaction with management and plant growth processes (Leakey *et al*., 2009) and one of the largest uncertainties in terrestrial biosphere impact models (Friend *et al*., 2014; Rosenzweig *et al*., 2014).

Adaptation and development strategies can profit from information about the overlap of multiple impacts and their mutual constraints (Conway, 2011; Lemos *et al*., 2012). We can identify hotspots of climate change impacts in sub-Saharan Africa, irrespective of the large uncertainties in projections of climate change patterns and thus of climate change impacts. The spatial overlap of regions with high exposure to climate change impacts, high poverty rates, and high population densities as in Malawi, Mozambique, Zambia, Zimbabwe, and in the Lake Victoria region is of particular concern and demands special attention on adaptation measures and development policies. These regions require significant support in coping with climate change and in development under uncertain environmental conditions.

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Author Contribution

CM, KW, AB, JH prepared data and modeling tools. CM designed the study, analyzed data, and wrote the article with contributions from all authors.

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Supporting Information

Appendix S1. Climate inputs and bias correction methods.
Appendix S2. Supplementary Figures S1–S11.