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Assessment of future agricultural conditions in southwestern Africa using fuzzy logic and high-resolution climate model scenarios

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Abstract
Climate change is expected to have a major impact on the arid savanna regions of southwestern Africa, such as the Okavango Basin. Precipitation is a major constraint for agriculture in countries like Namibia and Botswana and assessments of future crop growth conditions are in high demand. This GIS-based approach uses reanalysis data and climate model output for two scenarios and compares them to the precipitation requirements of the five most important crops grown in the region: maize, pearl millet, sorghum, cassava and cow pea. It also takes into account the dominant soil types, as plant growth is also limited by nutrient-poor soils with unfavorable physical and chemical properties. The two factors are then combined using a fuzzy logic algorithm. The assessment visualizes the expected shifts in suitable zones and identifies areas where farming without irrigation may experience a decline in yields or may even no longer be possible at the end of the 21st century. The results show that pearl millet is the most suitable crop in all scenarios while especially the cultivation of maize, sorghum and cow pea may be affected by a possible reduction of precipitation under the high-emission scenario.

Zusammenfassung
Der globale Klimawandel beeinflusst die ariden Savannengebiete im südwestlichen Afrika, wie die Okavangoregion, auf vielfältige Weise. Besonders die geringen Niederschläge schränken die Landwirtschaft in Ländern wie Namibia und Botswana bereits in der Gegenwart erheblich ein. In dieser GIS-basierten Studie werden langjährige Niederschlagsprognosen zweier hochaufgelöster Klimaszenarien mit dem Wasserbedarf der fünf wichtigsten Nutzpflanzen der Region – Mais, Perlhirse, Mohrenhirse, Maniok und Augenbohne – verglichen. Berücksichtigt werden auch die vorherrschenden Bodentypen, die ebenfalls eine Einschränkung für die landwirtschaftlichen Erträge darstellen. Die beiden Faktoren werden mit Hilfe eines Fuzzylogik-Algorithmus kombiniert. Auf diese Weise wird veranschaulicht, wie sich die Zonen optimaler Wachstumsbedingungen bis zum Ende des 21. Jahrhunderts potentiell verschieben werden und wo ein Anbau ohne künstliche Bewässerung unter Umständen nicht mehr möglich sein wird. Die Ergebnisse deuten darauf hin, dass in allen Szenarien Perlhirse zum Anbau in der Region am besten geeignet ist. Der Anbau von Mais, Mohrenhirse und Augenbohnen ist im hohen Emissionsszenario von einem Rückgang des Niederschlages betroffen und die klimatisch günstigen Zonen verschieben sich nach Norden.

Keywords Land evaluation, climate change, Angola, Namibia, Botswana, Okavango

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1. Introduction

Recently, the Intergovernmental Panel on Climate Change (IPCC) released its fifth assessment report on climatic changes and their likely impacts. In Africa, particularly in the more arid regions, temperature is expected to rise faster than the global land average. Depending on the emission scenario, warming projections of 2 to 6 °C by the end of the century have been calculated, alongside decreasing mean precipitation and shorter wet periods in southwestern Africa (*Niang* et al. 2014). This means that already existing stress on water resources will be amplified and shorter growing seasons and lower yields could negatively affect agricultural production in many African countries, therefore compromising food security. In many parts of the Okavango catchment, the suitability for crop growth is already low because of the dry climate and unproductive soils. Until the end of the 21st century, the cultivation of certain crops may be further reduced as precipitation falls below their tolerance limits. Thus, the guiding question of this paper is: How will climate change impact the agricultural suitability for the most important crops grown in the study area? The publication presents the results of a GIS-based analysis comparing the expected precipitation decline in southwestern Africa until the end of the 21st century with water tolerance levels of the five main crops grown in the region: maize, pearl millet, sorghum, cassava and cow pea. The corresponding shifts in suitability are assessed for both a medium-low (RCP4.5) and a worst-case (RCP8.5) emission scenario, which are identical to those used by the IPCC. Furthermore, the dominant soil types are taken into account, as soils with low fertility pose a further constraint on agriculture. The study area can be characterized as a poor data region, as information on physical and chemical soil properties is extremely limited. This poses restrictions on conventional land evaluation techniques used in other studies (*Bonfante* and *Bouma* 2015, FAO 2007). Therefore, the dominant soil type is used as an approximation of the suitabil-

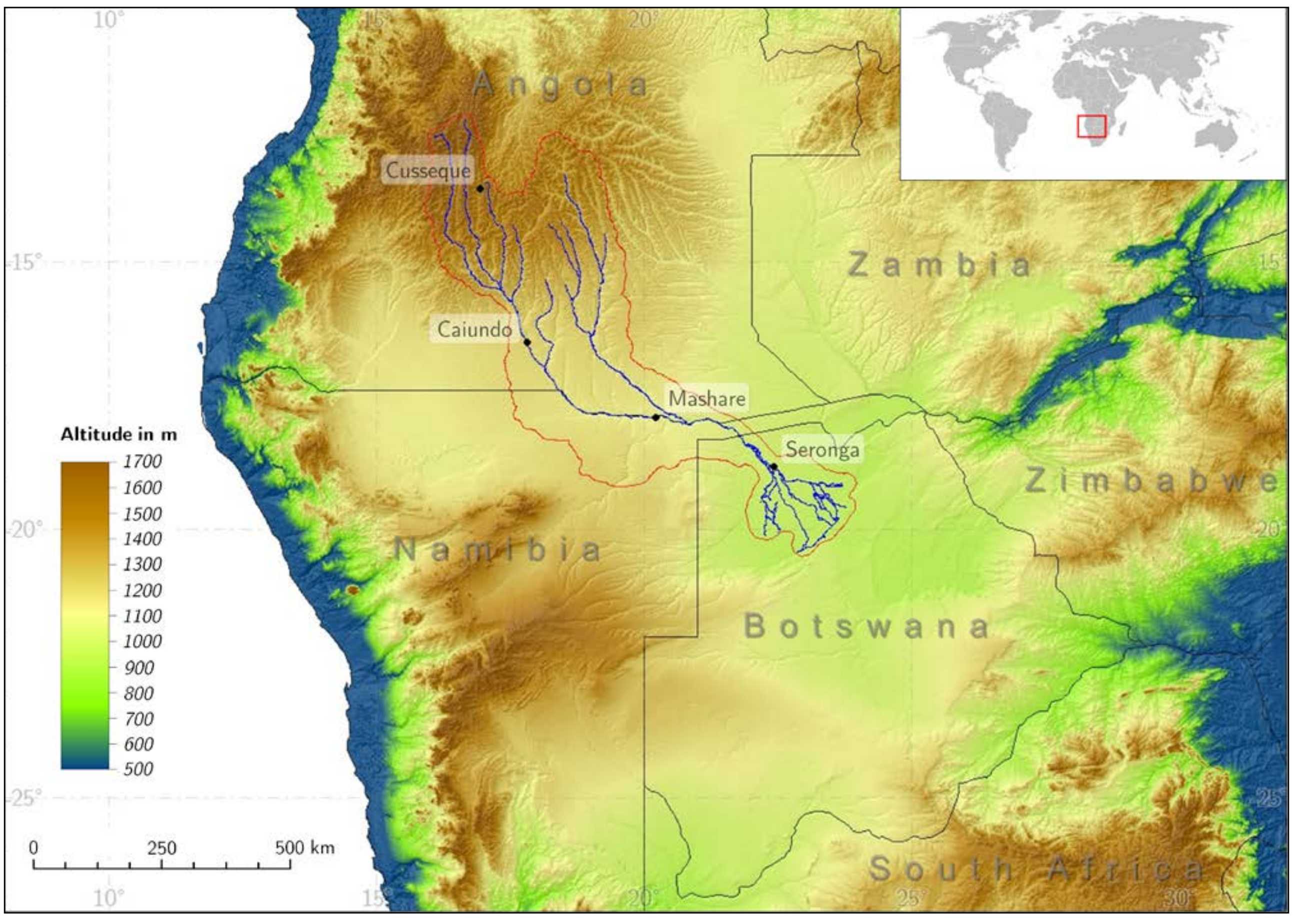

Fig. 1 Map of the study area in southwestern Africa with an underlying digital elevation model. The catchment of the Okavango River is marked red and four study sites of the TFO project are highlighted.

ity of the soil to support crop growth. The assessment is structured as follows: First, the study area with its environmental and socio-economic characteristics is introduced. Second, the datasets used for the comparison of climate conditions, crop precipitation requirements and soil types are described. Then the resulting spatial shifts of suitable zones are analyzed. Finally, strengths and weaknesses of the approach are discussed and a future outlook is given. The paper aims at filling the knowledge gap between global climate change and regional impacts as well as making the spatial dimension of these impacts visible.

2. Study area

The study area is situated in southwestern Africa, covers a domain from longitude 8° to 32° and latitude 10° to 27° and contains parts of seven different countries. The analysis is conducted within the framework of the Future Okavango (TFO) project, therefore a special focus lies on the catchment of the Okavango River, shared between the three riparian countries of Angola, Namibia and Botswana. While Angola had to endure a 27-year civil war that only recently ended in 2002, Namibia and Botswana are considered strongholds of democracy, economical and political stability in Africa and are also among the least densely populated countries in the world. The Okavango River is called the "lifeline"' of the region (*Mendelsohn* and *El Obeid* 2004) as it provides water in an otherwise largely very arid environment, and a considerable number of people in the three riparian states directly or indirectly derive their livelihoods from it. Originating in the humid Bié Plateau of Central Angola (*Fig. 1*), the river flows southeast, forms the border between Namibia and Angola for 400 kilometers, crosses Namibia's Caprivi Strip and, once having reached Botswana, it disperses into the Okavango Delta, a complex series of heavily vegetated channels and shallow basins. Elevation drops from 1850 m a.s.l. to just 940 m a.s.l., so the Basin can be subdivided into three prevalent landscape units, the Angolan highlands in the north, the lowland in the south and the delta region in Botswana (*Wehberg* and *Weinzierl* 2013). Large areas of this wetland, with its numerous islands, get flooded each year. 97 percent of the annual inflow into the delta is lost to evapotranspiration.

Located at the southern edge of the tropical zone, the Okavango catchment is characterized by a hot subtropical climate (category Bsh in the Köppen classification) with high annual mean temperatures ranging from 18 °C in the extreme north-west of the catchment to 26 °C in the very south due to decreasing cloud cover and the topographic influence of the Kalahari Basin (*Weber* 2013, *Jones* et al. 2013). Accordingly, potential evapotranspiration increases to the south with highest rates in the summer (*Mendelsohn* and *El Obeid* 2004). Precipitation in the study area shows a gradient from around 1,400 mm in the humid Angolan highlands, where about 95 percent of the runoff is generated, to less than 500 mm in the semi-arid southern part (*Weber* 2013). While the interannual variability of temperature is low, it is very high for rainfall. Two distinct seasons can be identified, a wet season in the austral summer from December to February and a dry season in the austral winter. This is due to the subtropical high pressure zone bringing in dry air from the south and the intertropical convergence zone bringing in moist air from the north (*Mendelsohn* et al. 2002).

Corresponding to the climate gradient, the northern part of the catchment is dominated by Miombo forests and open grassland and dwarf shrubs in the river valleys. The middle reaches are characterized by extensive woodlands on Kalahari sands while the southern part predominantly features thornbush savannah, shrub- and grasslands (see *Photo 1*) as well as some mixed woodland (*Revermann* and *Finckh* 2013). The delta region is dominated by seasonally flooded grasslands and reedbeds.

The majority (77 percent) of the Okavango basin population is rural (*Wolski* et al. 2009) and where there are no alternative sources of income (such as tourism), people rely heavily on farming to derive their livelihood. There may be between 80,000 and 90,000 farming households along the river (*Mendelsohn* and *El Obeid* 2004) and subsistence agriculture (predominantly slash-and-burn shifting and semi-permanent cultivation as well as small communal farms) and pastoralism are prevalent economic activities in the study area. In contrast to commercial agriculture, the crops are mainly consumed at home, sold at local markets or stored for possible use in years with bad harvests. Nevertheless, there are some ambitions to intensify the farming and develop large-scale green schemes, especially on the Namibian side of the river, and large tracts of forest have been cleared for farmland (*Mendelsohn* et al. 2002, *Schneibel* et al. 2013, *Röder* et al. 2014). The main crop products grown in the region are maize (*Zea mays*), cassava (*Manihot es-*

Photo 1 Typical xeric shrubland in northern Namibia (picture taken in March, at the end of the wet season) with usually less than 500 mm precipitation per annum (Photo: T. Weinzierl)

culenta, also called manioc), pearl millet (*Pennisetum glaucum*, locally called mahangu), sorghum (*Sorghum bicolor*) and cow pea (*Vigna unguiculata*) (*Domptail* et al. 2013, *Kowalski* et al. 2013, *Große* et al. 2013). Although the nutrient value of cassava is low, it is widely used as staple food. While it grows and can be harvested over three or four years, the other crops are replanted each year (*Mendelsohn* and *El Obeid* 2004). Mix and dominance of different crops vary across the basin and generally follow the gradient of rainfall from north to south. While in the wetter northwestern Cubango sub-basin maize is the main crop, supplemented by cassava, the latter predominates in the Cuito sub-basin, where it is supplemented by maize and vegetables. Moving southeast, maize and cassava gradually decline in importance and are increasingly replaced by pearl millet. This is on the one hand due to the widespread poor quality sandy soils, but also due to climatic factors. While farmers in Angola can often plant more than once a year, this is rarely the case for those in the southern part of the catchment (*Mendelsohn* and *El Obeid* 2004). Farmers in the delta region practice a flood recession system called onaka or molapo farming. They grow about equal proportions of millet and maize, but plant them in the low-lying, clayey soils of the floodplains because these are comparatively fertile (*Mendelsohn* and *El Obeid* 2004). The vast majority of produce in the study area, though, is grown on dryland fields depending on rainfall for moisture, and while high temperatures are unproblematic for most crops, timing and lack of precipitation is a major constraint for crop growth in the region. Namibia is one of the driest countries in the world without any perennial rivers originating on its territory. Due to these extreme climatic and hydrologic conditions, most agricultural activity in the country happens in its northernmost parts along the border with Angola. Even then, it is comparatively unproductive and risky when it is relied upon as the sole source of income. Since domestic production cannot cover the cereal requirements, maize is also imported from South Africa (*Mendelsohn* et al. 2002). According to a recent study by *Ray* et al. (2015), climatic variations explain up to 75 percent of maize yield variations in the region, a reason why long-term estimates of climate variables are in high demand.

As in many other regions in Africa, soils in the study area consist predominantly of sandy, erosion-prone Arenosols, that have a low water- and nutrient-holding capacity and allow only marginal yields without irrigation. Other soil types that can be found are the gravelly Leptosols as well as Fluvisols and Gleysols in the floodplains of the Okavango River and some saline soils (Solonchaks and Solonetz) surrounding the Etosha depression (*Dijkshoorn* and *van Engelen* 2003).

3. Data and Methods

Climate observations for southwestern Africa, especially Angola, are relatively scarce and often of low quality with only very short measured periods. This is mostly due to historic reasons such as the decades of civil war in parts of the catchment. The few existing historical climate records show an increase in temperature in the catchment since the late 1970s (*Weber* 2013). The IPCC furthermore expects prolonged periods of drought due to reduced, more erratic precipitation and increased evapotranspiration (*Boko* et al. 2007, *Niang* et al. 2014). In the recent years, General Circulation Models (GCM) have emerged as a tool to predict large-scale climatic conditions and assess the impacts of anthropogenic loading of the atmosphere with greenhouse gases. These models undergo constant improvement and today reach horizontal resolutions between 100 and 300 km. However, it will not be possible to compute scales of 50 km or less with a Global Climate Model accurately in the near future (*Spekat* et al. 2008). To enhance the resolution, a common practice is therefore to couple the GCM with a nested dynamical model (RCM – Regional Climate Models) that simulates climatic variables of a certain region through the laws of physics. For this study, a combination of the ECHAM6 General Circulation Model (*Stevens* et al. 2013) with the regional model REMO (*Jacob* 2001) for monthly average values was used. *Hänsler* (2011) showed that REMO well reproduces the main temporal and spatial climatic features of the southern African region including the strong seasonality and large interannual variability of rainfall patterns and therefore concludes that the model is suitable for climate studies in the region despite some coastal warm bias. The output underwent a regionalization scheme (*Weinzierl* et al. 2013, see *Fig. 2*) to reach a target resolution of 30 arc seconds (1 km) and a simple multiplicative correction to account for a slight overestimation of precipitation by the model. Two IPCC scenarios called RCP (Representative Concentration Pathways) were selected based on their coverage of possible future greenhouse gas emis-

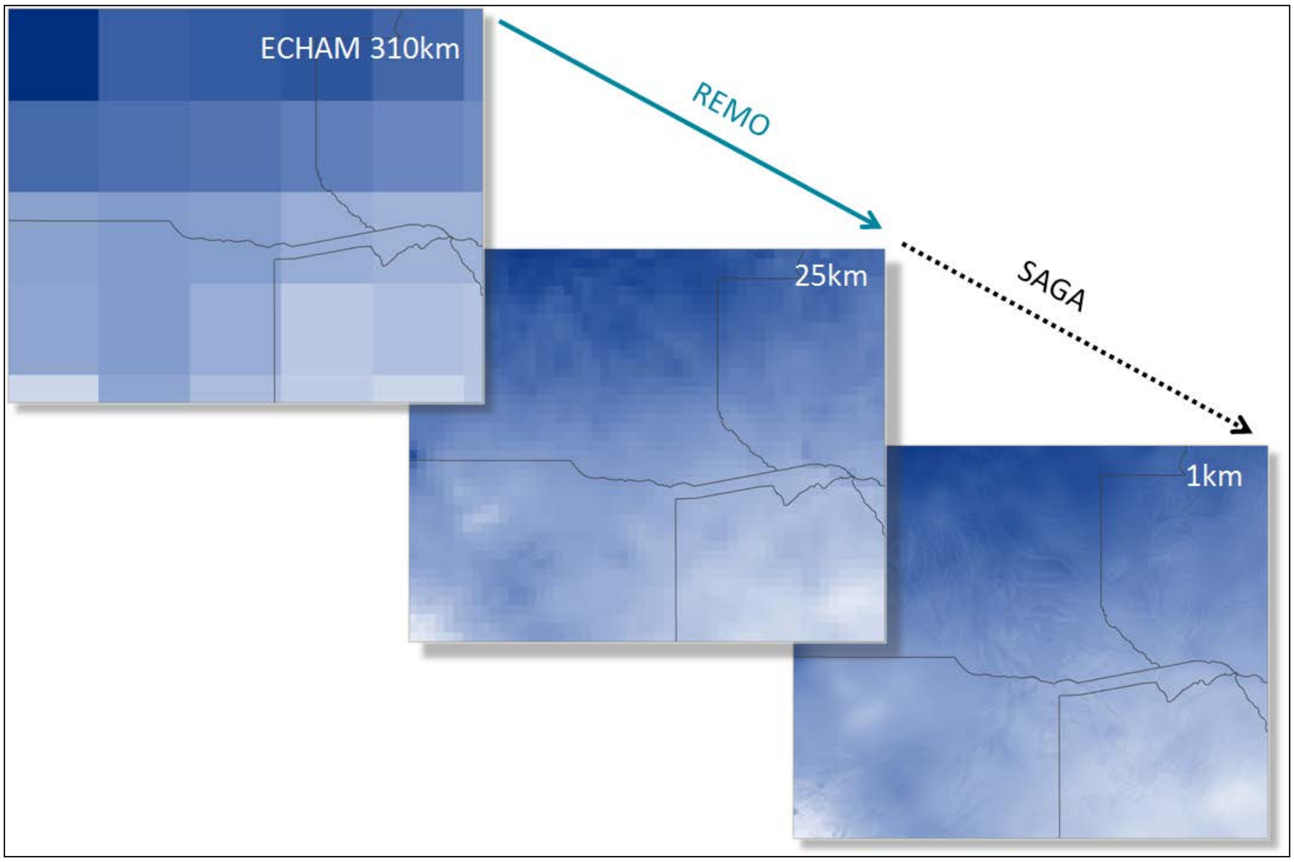

Fig. 2 Processing of the precipitation scenarios from the coarse GCM resolution to the final resolution of 1 km

Table 1 Annual precipitation requirements of the five main crops of the Okavango catchment (FAO 2014)

Plant	**Absolute min**	**Optimal min**	**Optimal max**	**Absolute max**
	mm			
Maize (*Zea mays*)	400	600	1200	1800
Pearl millet (*Pennisetum glaucum*)	200	400	900	1700
Sorghum (*Sorghum bicolor*)	300	400	600	700
Cassava (*Manihot esculenta*)	500	1000	1500	5000
Cow pea (*Vigna unguiculata*)	300	500	1500	4100

sions. RCP4.5 represents a medium-low and RCP8.5 a high scenario, in which the values 4.5 and 8.5 indicate the projected increase in radiative forcing (W/m^2) until the year 2100 (*Meinshausen* et al. 2011).

Because of the uncertainties inherent in long-term climate change projections, it is customary to work with sufficiently long time spans of 30 years or more. We therefore compare the modeled average precipitation for the years 2071-2100 with a reference period from 1980-2009. Until the end of the 21st century, the mid-range scenario (RCP4.5) shows a moderate increase in annual mean temperature between 2.2 and 2.8 °C accompanied by a precipitation decrease between 3 and 11 percent averaged over the whole study area. For the worst-case scenario (RCP8.5), a temperature increase of between 4.8 and 5.7 °C is estimated, while the precipitation decrease ranges between 9 and 32 percent. Both scenario runs indicate that the southern part of the basin is likely to be more affected by temperature increase and precipitation decrease than the northern part, while precipitation is already very unevenly distributed. The annual precipitation requirements for five crops were obtained from the ECOCROP database (FAO 2014). They include optimal and absolute minimums and maximums (see *Table 1*).

Table 2 Summary of most common soil types in the domain and assigned suitability ratings from 0 to 1 based on IUSS Working Group WRB (2006)

Soil type	**Rating**	**Description**
Arenosol	0.4	Coarse, sandy soils, only productive if irrigated and fertilized
Calcisol	0.4	Limey soils, only productive if irrigated and fertilized
Cambisol	0.6	Suitable for arable farming
Chernozem	1.0	Very fertile soils
Fluvisol	0.7	Good natural fertility
Ferralsol	0.2	Weathered, nutrient-poor and relatively unproductive
Gleysol	0.8	Very productive if properly drained and managed
Leptosol	0.1	Shallow, rocky soils almost unsuitable for arable farming
Lixisol	0.6	Suitable for arable farming, good yields when fertilized
Luvisol	0.9	Very fertile soils suitable for arable farming
Podzol	0.1	Low nutrients, low available moisture, unattractive for arable farming
Solonchak	0.2	High salt concentration, limited potential for arable farming
Solonetz	0.2	Clayey, deteriorated soils with limited potential for arable farming

The spatial analysis was conducted in SAGA-GIS (System for Automated Geoscientific Analyses), a cross-platform open source Geographic Information System software developed by the departments of Physical Geography in Göttingen and Hamburg (*Conrad* 2006). Since the mean temperature requirements of none of the crops were exceeded in the climate scenarios, they were regarded as unproblematic and the focus lies on precipitation and soils as the main constraints. The effects of the precipitation decrease on the cultivation of crops were analyzed using a fuzzy logic approach. First, the precipitation scenarios were fuzzified according to the optimal and absolute water requirements shown in *Table 1* to derive the climatic suitability in cell values from 0 (not suitable at all) to 1 (very suitable). As the model is a simplification of reality, a linear relationship was assumed between the absolute and optimal values.

Soils pose a second very important limitation to crop growth in the region, therefore the predominant soil type was obtained from the SOTERSAF database (*Dijkshoorn* and *van Engelen* 2003) and included in the analysis. The soil types were rated by the authors according to their suitability for agricultural use without additional irrigation or fertilization based on the evaluations of IUSS Working Group WRB (2006) and also fuzzified to values between 0 and 1 (see *Table 2*). For Zambia, the Democratic Republic of the Congo and some protected areas such as the Etosha, Skeleton Coast and Tsau//Khaeb (Sperrgebiet) national parks, no soil data were available at the time of the study and they were therefore excluded. In *Figure 3*, the x-axis represents low to high values of precipitation (blue) and soil fertility (green) while the y-axis illustrates the resulting suitability for crop growing. The two fuzzified datasets were then combined using the "AND Intersection" algorithm with the min-operator (red) in the Fuzzy Logic module of SAGA-GIS. This algorithm assigns the lowest cell value from the two different inputs, precipitation and soil fertility. This means that if in one cell cultivation is not possible at all because of one of the factors, the output will be 0. When one of the factors is optimal, the other factor determines the overall suitability. Or in other words, the agricultural potential can be only as high as the worst constraining factor at a certain location.

4. Results

The climate model scenarios indicate that the climatic suitability at present is already limited for most crops in the region. Furthermore, a large portion of the study area is likely to experience a precipitation decline of up to 20 % until the end of the century. This decline is more distinct in the RCP8.5 scenario than

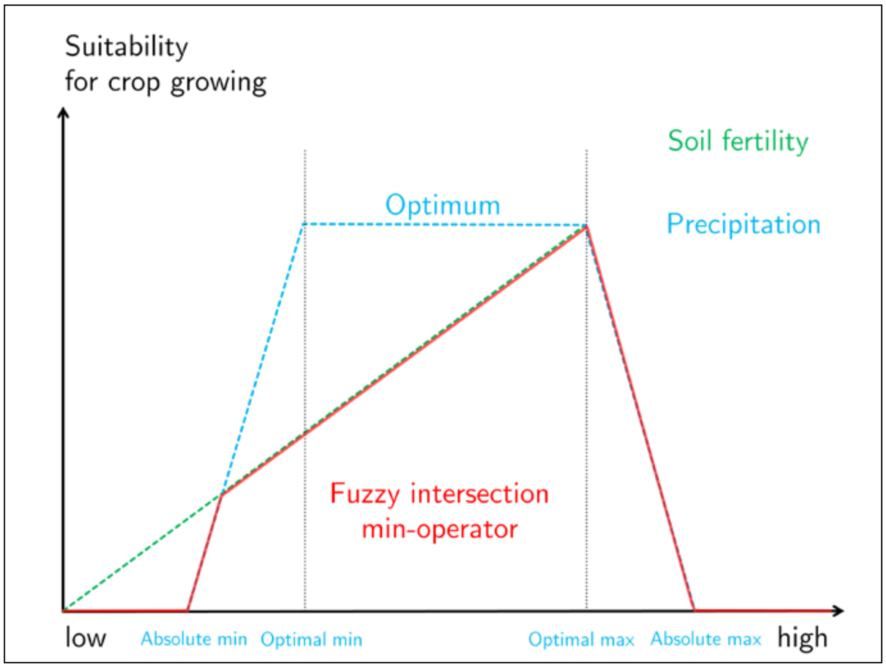

Fig. 3 The fuzzy logic algorithm (red) describes the constraining factor and combined suitability for crop cultivation at each stage. When precipitation is optimal, soil fertility determines the overall suitability.

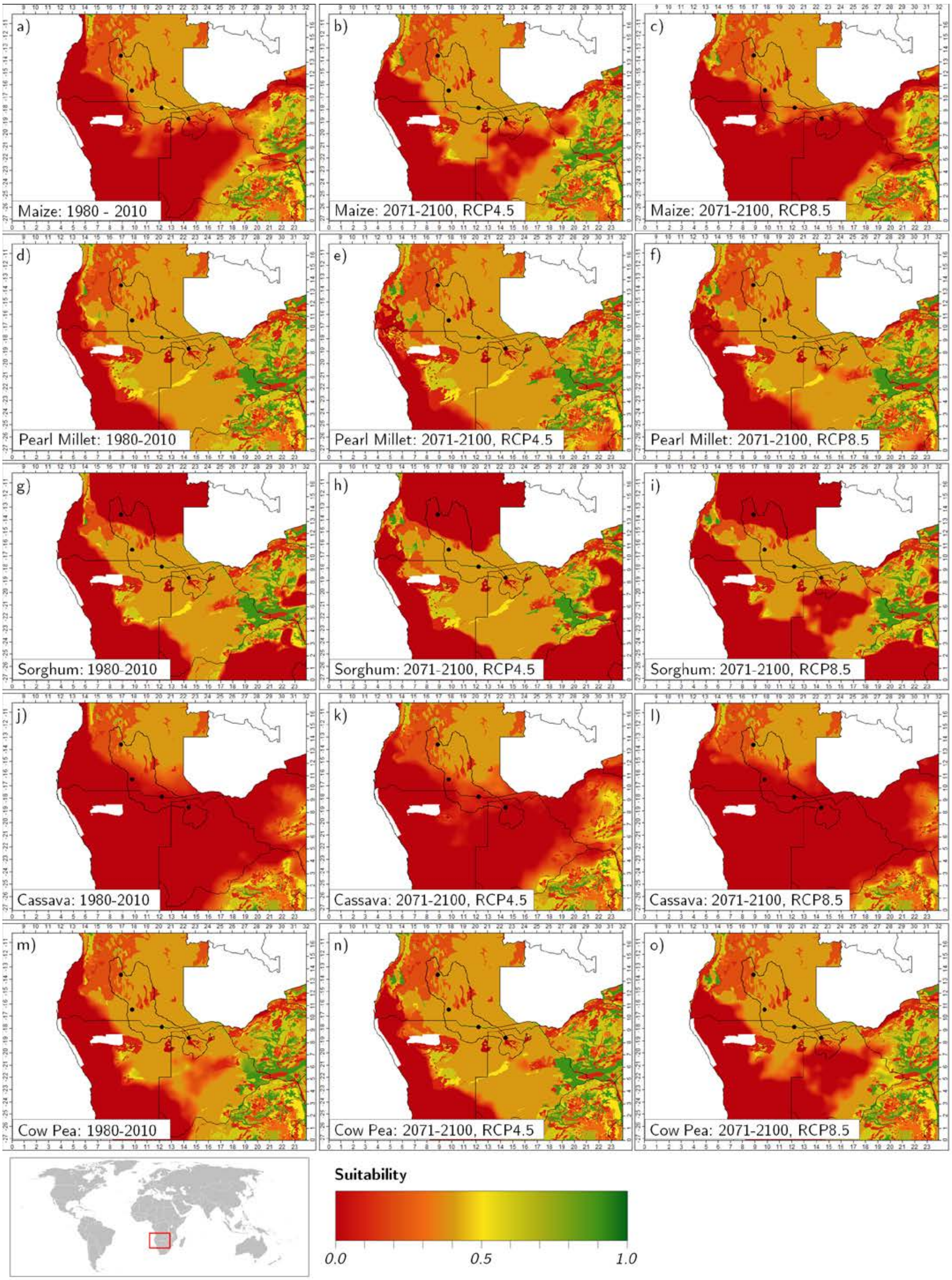
a)
Maize: 1980 - 2010
b)
Maize: 2071-2100, RCP4.5
c)
Maize: 2071-2100, RCP8.5
d)
Pearl Millet: 1980-2010
e)
Pearl Millet: 2071-2100, RCP4.5
f)
Pearl Millet: 2071-2100, RCP8.5
g)
Sorghum: 1980-2010
h)
Sorghum: 2071-2100, RCP4.5
i)
Sorghum: 2071-2100, RCP8.5
j)
Cassava: 1980-2010
k)
Cassava: 2071-2100, RCP4.5
l)
Cassava: 2071-2100, RCP8.5
m)
Cow Pea: 1980-2010
n)
Cow Pea: 2071-2100, RCP4.5
o)
Cow Pea: 2071-2100, RCP8.5
Suitability
0.0
0.5
1.0

Fig. 4 Natural suitability for the five main crops derived from precipitation reanalysis (left column) and two climate model scenarios (middle and right column). The Okavango catchment is outlined grey and four local study sites of the Future Okavango Project are marked black.

in RCP4.5 and more pronounced in the southern parts than in the north. As extremely fertile soils like Chernozems are rare in southern Africa, the maximum suitability rating of 1 is hardly reached and widespread areas only feature low to moderate suitability for crop growth. Our data suggest that the areas with the highest agricultural potential can be found at the eastern edge of the domain, in eastern Botswana, Zimbabwe and the South African province of Limpopo. Maize, pearl millet and cow pea can be cultivated in most of these areas today and the results suggest no major changes (*Fig. 4*). South of the Okavango catchment and in parts of the delta region, maize is not suitable at present. Under the RCP4.5-scenario, a slight increase in precipitation might enable cultivation in northeastern Namibia and parts of Botswana. RCP8.5 indicates a northwards shift of the suitable zone and therefore a decline in yields in the southern half of the catchment. As pearl millet is relatively drought-resistant, it can be grown in most parts of the study area except the extremely dry desert areas. Until the end of the 21st century, the climatic potential for growing pearl millet will most likely remain moderate under both emission scenarios. Today, sorghum is suitable for widespread regions in the center of the study area. Under RCP4.5, only slight changes are projected while under RCP8.5 especially central Botswana is affected by a decrease in mean precipitation. Cassava is at present only grown in the very northern part of the catchment. While the mid-range projection shows a slight increase in suitable area, the worst-case scenario shows no major changes compared to the present state. The current suitability for cow pea is moderate in most parts of the study area. RCP4.5 suggests a slight increase along the Namibian-Angolan border and in the center of Botswana. The same regions are affected negatively in the RCP8.5-scenario.

5. Discussion

Previous studies (*Paeth* et al. 2005, *Paeth* et al. 2009, *Hänsler* 2011) have emphasized the good performance of REMO in terms of reproducing the basic seasonal features of the African climate. Nevertheless, the approach should in the future be enhanced and cross-checked with a wider array of General Circulation Models and Regional Climate Models to account for uncertainties inherent in the models and their initial conditions. Four local study sites along the physico-ecological gradient with increasing annual mean temperature and decreasing precipitation have been assigned by the TFO project participants: Cusseque and Caiundo in Angola, Mashare at the Namibian-Angolan border and Seronga at the panhandle of the delta in Botswana (see *Fig. 4*). At these locations, the current farming systems and crops were assessed within the project; these assessments confirm the results for the present state. Since the analysis assumes that no irrigation or fertilization is taking place, there may also be "unsuitable" regions where a cultivation is indeed taking place in reality and the results are not to be mistaken for an exact portrayal of the actual situation. It is, however, an approximation of the natural preconditions and their development in the future. In the center of the study area, poor soils are the limiting factor for farming while especially to the south, precipitation poses the main restriction. Due to the prevalence of the sandy Arenosols, even optimal water provision only leads to a medium suitability in the major part of the study area. Note that the presented approach simplifies a number of processes and interrelations, including the linear gradient of suitability between absolute and optimal zones of precipitation, extreme temperature values and effects of evapotranspiration that are not yet incorporated. Furthermore, different cultivation forms may not only result from but also in return have an influence on suitability. Soil is a dynamic system and its properties might also change over time as a result of changing climate conditions (*Bonfante* and *Bouma* 2015). The FAO framework for land evaluation (FAO 2007) provides the basis for comparable analyses of land suitability (*Bonfante* and *Bouma* 2015, *Elaalem* et al. 2011, *Elaalem* 2012, *Huynh* 2008, *Arshad* et al. 2013a, *Arshad* et al. 2013b, *Keshavarzi* et al. 2010). While for some regions of the world, detailed soil survey information allows for the inclusion of individual physical (texture, depth, stoniness) and chemical (pH, salinity, organic matter) properties in analyses, most of Africa can be considered a poor data region. *Arrouays* et al. (2014) estimate that only about one third of the global land area has been significantly mapped in respect to soil data, and most of this mapping was conducted before the widespread use of digital methods. Unfortunately, the study area of this paper is part of the two thirds of the world where hardly any more detailed data besides the soil type are available. Therefore, an agro-ecological zoning (FAO 2007) is not possible using detailed soil properties, and the dominant soil type has to be used as a proxy. The lack of input data, though, emphasizes the relevance of finding suitable methods to handle this problem and possibly transfer the approach to other areas of interest. While rating soil types in order of suitability based on expert knowledge limits comparability with other studies, it enables analyses with limited input data, which is an advantage in regions without detailed information on soil properties. The presented approach furthermore utilizes fuzzy logic as a means to quantify and combine different datasets. Fuzzy approaches are increasingly used by the scientific community to handle uncertainties, incomplete information and class memberships that are approximate rather than precise (*Malczewski* 2006, *Chaddad* et al. 2009, *Delgado* et al. 2009, *Keshavarzi* et al. 2010, *Elaalem* et al. 2011, *Elaalem* 2012). While, like every model, it is still an idealization of reality, one of the strengths of fuzzy logic is that it requires only moderate computing resources. Furthermore, it is able to reproduce the continuous transitions found in nature as opposed to the sharp thresholds assumed by boolean mapping methods, which have been criticized by a number of authors (*Burrough* 1989, *Baja* 2001, *Delgado* et al. 2009, *Keshavarzi* et al. 2010). Recently, fuzzy logic was also introduced to the revised FAO land evaluation framework (FAO 2007); the FAO, in fact, recommends it for the classification of soil survey data. *Elaalem* 2012 emphasizes the richer overall picture and the continuous classes that benefit land evaluation by handling imprecise terms such as "slightly better" or "relatively dry". This way, spatial trends can be visualized and interpreted more realistically than with boolean methods.

6. Conclusion

This paper presents results of a spatially explicit analysis of future agricultural potential in southwestern Africa. It brings together climatic scenarios with data on the precipitation requirements of the five most important crops and the dominant soil types in the study area. The results suggest that climate change impacts vary significantly between different crops and emission scenarios. Pearl millet is the most suitable crop in most parts of the study area under both climate scenarios due to its drought resistance, while cassava has the most limited suitability. The mid-range-scenario potentially slightly expands the suitable zone for maize and cow pea. Under the high emission scenario especially maize, sorghum and cow pea may be affected by precipitation declines. Despite the obvious uncertainties inherent in the approach, it constitutes a beneficial outlook on future agricultural constraints for stakeholders and decision-makers in the region.

While the analysis is already showing comprehensible results and can be transferred to other study areas without difficulty, some improvements remain advisable. In future assessments, the analysis can be enhanced with a more diverse set of climate models, more crops as well as the length of the growth period and minimum and maximum temperatures as additional factors, which was not feasible in the context of this study. It would also be imaginable to conduct a comparable analysis for the water requirements of livestock, although in this case a number of other factors would have to be taken into account. For assessing developments in the region and improving the current data situation, continuous monitoring of climate variables is advisable. Furthermore, a standardization of the soil type ratings would make comparisons with other poor data regions easier. To cope with the impacts of climate change, the development of mitigation and adaptation strategies is essential especially as the analysis suggests considerable differences between the two climate scenarios.

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