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Quantifying trade-offs between future yield levels, food availability and forest and woodland conservation in Benin

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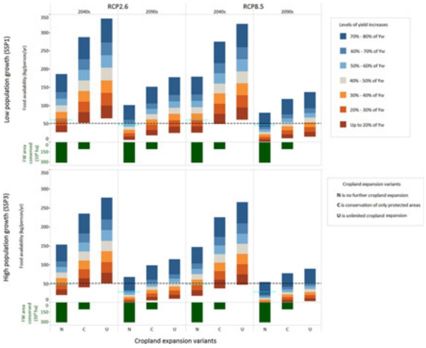
HIGHLIGHTS

- Water-limited yield potentials are likely to decrease considerably due to climate change.
- Substantial levels of yield gap closure will be required to maintain current levels of food availability.
- Forests and woodlands are likely to come under enormous pressure from cropland expansion.

GRAPHICAL ABSTRACT



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ABSTRACT

Meeting the dual objectives of food security and ecosystem protection is a major challenge in sub-Saharan Africa (SSA). To this end agricultural intensification is considered desirable, yet, there remain uncertainties regarding the impact of climate change on opportunities for agricultural intensification and the adequacy of intensification options given the rapid population growth. We quantify trade-offs between levels of yield gap closure, food availability and forest and woodland conservation under different scenarios. Each scenario is made up of a combination of variants of four parameters i.e. (1) climate change based on Representative Concentration Pathways (RCPs); (2) population growth based on Shared Socioeconomic Pathways (SSPs); (3) cropland expansion with varying degrees of deforestation; and (4) different degrees of yield gap closure. We carry out these analyses for three major food crops, i.e. maize, cassava and yam, in Benin. Our analyses show that in most of the scenarios, the required levels of yield gap closures required to maintain the current levels of food availability can be achieved by 2050 by maintaining the average rate of yield increases recorded over the past two and half decades in addition to the current cropping intensity. However, yields will have to increase at a faster rate than has been recorded over the past two and half decades in order to achieve the required levels of yield gap closures by 2100. Our analyses also show that without the stated levels of yield gap closure, the areas under maize, cassava and yam cultivation will have to increase by 95%, 102% and 250% respectively in order to maintain the current levels of per capita food availability. Our study shows that food security outcomes and forest and woodland conservation goals in Benin and likely the larger SSA region are inextricably linked together and require holistic management strategies that considers trade-offs and co-benefits.

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1. Introduction

Substantial increases in crop production are needed to meet the growing food demand of the population of sub-Saharan Africa (SSA), which is projected to double by 2050 compared to 2015 estimates (UN, 2015). For example, the cereal demand for 10 countries in SSA (which comprise 54% of total SSA population) is projected to triple by 2050 compared to 2010 estimates, assuming an average population growth of 1.5% per annum and modest dietary changes in these countries (van Ittersum et al., 2016). Currently in SSA, about 97% of cropland area is under rainfed cultivation (You et al., 2011) and productivity levels for major food crops, which are the lowest in the world, are inadequate to meet projected demand (Alexandratos and Bruinsma, 2012; van Ittersum et al., 2016).

In recent decades, the slow rate of increase in productivity levels of major crops has led to conversion of vast areas of forests and woodland to croplands (Pretty et al., 2011). Over the past 25 years (1990–2015), forest and woodland extent in SSA has been declining (Sloan and Sayer, 2015) despite the reduction in the rate of net global deforestation (FAO, 2015b). For example, between 2010 and 2015 there was a 1.1% (50,000 ha per annum) decrease in forest area in Benin (FAO, 2015b). Forests and woodlands in SSA provide, however, essential ecosystem services of local, national and global benefits. Forests and woodland areas of SSA are essential for among others biodiversity conservation (Chidumayo and Gumbo, 2010), water flow regulation (Duku et al., 2016), wood and non-wood forest products, desertification control and soil amelioration, carbon sequestration (Lal, 2004; UNFCCC, 2006), and grazing opportunities for livestock (Judex and Thamm, 2008).

To meet the dual objectives of increasing crop production, and consequently ensuring food security on one hand, and protecting natural ecosystems by limiting cropland expansion on the other hand, agricultural intensification is considered most desirable (Palm et al., 2010; Foley et al., 2011; Pretty et al., 2011; Garnett et al., 2013; Hall and Richards, 2013). Yet, several important questions need to be addressed for major food crops at national and sub-national levels in SSA. Will intensification measures alone be adequate to meet growing food demand? Moreover, how will climate change affect the degree of success of intensification measures and how much additional land may be required? Even without climate change, a recent study showed that it will not be feasible to meet 2050 SSA cereal demand on existing production cropland by yield gap closure alone (van Ittersum et al., 2016). Taking into account climate change in such analysis is important because there are biophysical limitations to yield increases imposed by temperature and water supply (Gornall et al., 2010; Hall and Richards, 2013; van Ittersum et al., 2013). West Africa in particular has been identified as a regional hotspot of climate change with climate departure from historical variability projected to occur faster than the global average (Diffenbaugh and Giorgi, 2012; IPCC, 2013; Mora et al., 2013).

Therefore, in this study we quantify trade-offs between levels of yield gap closure, per capita food availability, and forest and woodland conservation under different scenarios. Each scenario is made up of a combination of four variables i.e. (1) climate change based on Representative Concentration Pathways (RCPs); (2) population growth based on Shared Socioeconomic Pathways (SSPs); (3) cropland expansion with varying degrees of deforestation; and (4) different degrees of yield gap closure. We undertake these analyses for three major food crops in Benin i.e. maize, cassava and yam. Specifically, we analyse levels of yield increases and/or cropland expansion required to at least maintain per capita food availability for the decades 2041–2050 (2040s) and 2091–2100 (2090s) at baseline levels (i.e. 2001–2011). We are in no way positing that per capita availability of these crops was optimal for the period 2001–2011 even though for this period the average dietary energy supply adequacy, i.e. the ratio of dietary energy supply and dietary energy requirements, was 114% (FAO, 2016). Cereals, roots and tubers accounted for over 70% of the dietary energy supply in Benin over this period (FAO, 2016). These crops all are produced locally (FAO, 2016). Maize is the most widely cultivated cereal, and cassava and yam are the main root and tuber crops.

2. Methodology

2.1. Study area

Our study area covers the Ouémé river basin in Benin and the southwestern parts of the country that lie outside the river basin (Fig. 1). It covers an area of approximately 55,000 km^2 which is about half of the total area of Benin. Benin is divided into eight agricultural zones based largely on climate, soil type, elevation and different crops grown (MDR, 1998; FAO, 2015a). Six of these zones lie within our study area (Table 1 and Appendix 1). The total population in the study area is approximately 7 million which is 70% of the total population of the country (Bright et al., 2011). The proportion of the total population of the country that is undernourished is currently 7.5% (FAO et al., 2015). The study area is located in the sub-humid tropical region with aridity indices ranging between 0.50 and 0.65. Land use in the northern and central part of the study area is dominated by a mosaic of woodland savannah including tree shrubs and forest islands with relatively smaller cropland area. The southern part of the study area is relatively more urbanized and land use is dominated by large areas of small-scale rainfed agriculture and oil palm plantations. In addition to these dominant land use types, there are also grasslands, which cover <5% of the total area (Judex and Thamm, 2008). There are also large state-owned protected forests covering an area of about 6000 km^2 mainly in the northern and central part of the study area. The irrigation sector is poorly developed and the lack of irrigation water during the dry season is a major problem for many farmers (Giertz et al., 2012). Consequently, crop cultivation mainly takes place during the wet season. Due to land availability in the northern and central parts of the study area, residents from other parts of the country and neighbouring countries migrate to this region, which has caused expansion of agricultural areas and led to substantial deforestation (Judex and Thamm, 2008).

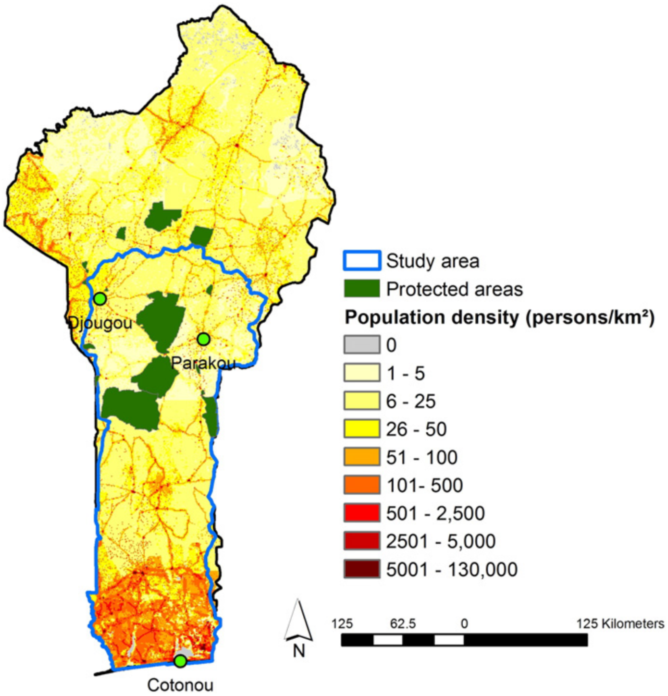

Fig. 1. Map showing current population density of Benin (Bright et al., 2011), our study area and protected areas.

Table 1
Shares of cropland area in agricultural zones used for cultivation of maize, cassava and yam (You et al., 2014).

Agricultural zones in the study area	Total cropland area in study area (ha)	Share of cropland area for each crop (%)		
		Maize	Cassava	Yam
Zone 3	58,100	20	3	9
Zone 4	48,927	7	11	5
Zone 5	321,449	25	8	14
Zone 6	140,965	39	25	<1
Zone 7	52,992	33	19	<1
Zone 8	73,571	57	16	2
Total	696,004			

2.2. Methodological framework

To quantify trade-offs between future yield gap closures, food availability and forest and woodland conservation, we performed scenario analyses for two time-periods i.e. 2041–2050 (2040s) and 2091–2100 (2090s). Each scenario is a combination of variants of four parameters: (1) climate change based on the Representative Concentration Pathways (RCPs); (2) population growth based on the Shared Socioeconomic Pathways (SSPs); (3) cropland expansion with varying degrees of deforestation; and (4) different levels of yield gap closure. For a similar approach, cf. Erb et al. (2016). Each scenario shows food availability per person for three staple foods and the forest and woodland areas that would be conserved in order to achieve that level of availability under conditions defined by these parameter variants and further conditions that are constant among all scenarios. The conditions that are assumed constant in all scenarios include (1) share of croplands areas used for the cultivation of a specific crop; (2) share of crops used as food; (3) dietary preferences and (4) the best lands in terms of soil moisture are used for the cultivation of these crops. The next four subsections (Sections 2.2.1 to 2.2.4) present a detailed description of our methodology.

2.2.1. Climate change and population growth

We used two contrasting climate change projections based on RCP2.6 and RCP8.5. For each RCP, we obtained downscaled precipitation, maximum and minimum temperature and solar radiation data for the 2040s and 2090s. The climate data were multi-model mean climate data of 17 General Circulation Models (see Appendix 2) obtained from the MarkSimGCM geoportal (Jones and Thornton, 2013). RCP2.6 is an emission pathway that leads to the lowest concentration levels of atmospheric greenhouse gases (Moss et al., 2010; IPCC, 2013). It represents a peak in greenhouse gas emissions before 2100 followed by a consistent decline throughout the rest of this century. RCP8.5 on the other hand, is characterized by increasing greenhouse gas emissions throughout this century leading to the highest concentration of atmospheric greenhouse gases by the end of this century (Moss et al., 2010; IPCC, 2013).

Future population estimates were based on SSP1 and SSP3 for 2050 and 2100 (Table 2) (O'Neill et al., 2013). The SSPs are a set of alternative reference assumptions about future socioeconomic development in the absence of climate policies. SSP1 depicts a development pathway characterized by rapid economic development especially in low-income countries leading to rapid technological development, increased resource use efficiency and low population growth; SSP3 depicts slow economic growth, slow technological development, low resource use efficiency and rapid population growth.

Table 2
Future population estimates in the study area (O'Neill et al., 2013). For the 2040s and 2090s decades, the population represents projections for 2050 and 2100 respectively. Current population in the study area is approximately 7 million (Bright et al., 2011).

	2040s	2090s
SSP1	8,200,000	14,700,000
SSP3	10,100,000	23,700,000

2.2.2. Cropland expansion

The total area of land currently under cultivation in the study area is about 700,000 ha of which 30% is used for maize cultivation, 13% for cassava cultivation and 8% for yam cultivation (You et al., 2014). Table 1 shows the disaggregated share of current cropland area in each of the eight agricultural zones. We defined three variants of cropland expansion involving varying degrees of conversion of forest and woodland savannah areas for crop cultivation by 2050 and 2100. The first, 'No cropland expansion', represents prioritization of forest conservation over cropland expansion. Therefore, the current cropland extent in the study area would be maintained, without further conversion of forest and woodland savannah area for crop cultivation. The second, 'Conservation of only protected areas' represents the situation where only forests and woodlands outside protected areas are permitted to be converted for crop cultivation. Hence, current regulations barring encroachment on protected areas will still be enforced. The third, 'Unlimited cropland expansion' represents the situation where all forests and woodlands including protected areas are permitted to be converted for crop cultivation.

For each variant of cropland expansion we assumed no change in shares of areas of the different crops in each agricultural zone. We acknowledge that for example trends over the past two decades indicate increase in maize area at the expense of sorghum in SSA, however, it is not clear how the share of each crop area in Benin will develop in the future. We also assumed that the best lands in terms of soil moisture availability in current and new croplands would be set aside for cultivation of maize, yam and cassava because these crops were the major crops in the study area (in addition to rice and cotton). Our assumptions were necessary because land use and land cover data available for the study do not have sufficient detail to allow for the differentiation of specific crops in the cropland areas.

2.2.3. Water-limited yield potential

Water-limited yield potential (Yw) is the maximum yield of a crop under conditions where only water supply is limiting, nutrients are assumed to be non-limiting and there is effective biotic stress control (Lobell et al., 2009; van Ittersum et al., 2013). Yw is influenced by soil properties especially rooting depth and root-zone water holding capacity (Lobell et al., 2009; van Ittersum et al., 2013). Water-limited yield represents the yield potential in rainfed cropping systems. Our approach for simulating Yw for the study area involved three steps: soil-water balance modelling to simulate spatio-temporal dynamics of soil moisture, crop growth simulation, and Yw upscaling. Because of inadequate data, we carried out the soil-water balance and crop growth simulation for only a part of the study area (Duku et al., 2015). Climatic and biophysical features in the study area in Duku et al. (2015) are largely representative for the whole study area of the present paper (Licker et al., 2010; HarvestChoice, 2011; van Wart et al., 2013; Claessens and van Wart, 2014). All simulations were carried out on gridded data at 1 ha spatial resolution.

We used the Soil and Water Assessment Tool (SWAT) to simulate the spatio-temporal dynamics of soil moisture content, required for Yw simulation. The SWAT model is a physically based, ecohydrological model that simulates the impact of land use and land management practices on the complete hydrological cycle in large complex watersheds with varying soils, land use and management conditions over a long period of time (Neitsch et al., 2009). The SWAT model has been calibrated and validated for the northern part of the study area in a previous study, Duku et al. (2015).

Simulated time-series of soil moisture content were used as input for the simulation of Yw, in addition to precipitation, temperature and solar radiation data. We utilized the AEZ crop growth model to simulate Yw. The AEZ crop growth model is based on Kassam (1977), Doorenbos and Kassam (1979) and Smith (1992). The AEZ crop modelling framework uses agronomic-based information in addition to spatially explicit biophysical datasets to simulate crop production potentials (IIASA/FAO, 2012). The model first calculates maximum attainable biomass and yield as determined by temperature and radiation regimes followed by computation of Yw based on precipitation and soil moisture dynamics (IIASA/FAO, 2012). In the AEZ crop growth model, the effect of increasing atmospheric carbon dioxide concentration on crop yield is accounted for by yield-adjustment factors (IIASA/FAO, 2012). For each crop, an iterative simulation of Yw with varying starts of growing season was undertaken and the maximum Yw in each grid cell (1 ha) was selected.

Simulated Yw were then upscaled to the entire study area based on delineation of Hydro-Climatic Response Units (HCRU). Given data constraints, such upscaling approaches are useful for extending coverage of estimates of Yw. In this study, each HCRU is a discretized landscape unit with homogenous land cover, soil type, slope (Neitsch et al., 2009) and in which the aridity index varies by not more than one standard deviation. The aridity index is the ratio of annual precipitation and potential evapotranspiration totals and represents the degree to which precipitation can satisfy vegetation water requirements (UNEP, 1993). The study area is located in the sub-humid tropical region with aridity indices ranging between 0.50 and 0.65 (mean of 0.59 and a standard deviation of 0.02). Grid cells in each HCRU, therefore, have similar climatic water balance and exhibit similar hydrological response in terms of soil moisture content. HCRUs identified in the northern part of the study area were matched to HCRUs identified in the rest of the study area and Yw were assigned to matching HCRUs.

2.2.4. Food availability

Food availability is one of the four key dimensions of food security (FAO, 1996). We computed per capita food availability for each studied crop under different combinations of RCPs, SSPs and cropland expansion scenarios. We first estimated potential cropping intensity based on the length of growing period. Under each combination of RCP and cropland expansion scenario, the potential area under cultivation was delineated into sequential double and single cropping zones based on the length of growing period (Duku et al., 2017). The cropping intensity was then computed based on Eq. (1). A cropping intensity of 1.5 implies that half of the total land area under cultivation can be used to grow two or more crops per year. For baseline conditions, we estimated cropping intensity based on harvested and physical areas (You et al., 2014).

$$C_i = 1 + (D_{CZ}/A_c) \tag{1}$$

where C_i is cropping intensity; D_{CZ} is total area that can grow two or more crops per year (ha); A_c is total area under cultivation (ha).

Part of the crop production is used as feed for livestock and poultry, seeds for cultivation, and other uses such as starch in the case of cassava. In addition, there are also postharvest and other forms of losses. We used the mean food component of total production over the baseline period for the computations of future food availability. Per capita food availability of each crop was then computed based on Eqs. (2) and (3).

$$T_p = Y \times P_a \times C_i \tag{2}$$

$$F_a = (k \times T_p)/\mathrm{Pop} \tag{3}$$

where T_p is total production of each crop in the study area (kg); Y is average yield of each crop (kg/ha); P_a is physical area for cultivation of each crop (ha); C_i is the cropping intensity; F_a is per capita food availability (kg/person/year); k is the proportion of total production that is used as food; Pop is total population of the study area (persons).

For each crop, we also calculated the average rate of yield increase over the period 1991–2014 and extrapolated the results into 2050 and 2100. We calculated per capita food availability based on these trends in yield increases in existing cropland areas.

3. Results

Fig. 2 shows that water limited yield (Yw) of maize is likely to decrease from 7.2 t/ha under baseline climatic conditions to 4.5 t/ha under RCP8.5 by 2100. Water-limited yield potential of cassava is also likely to decrease from 26.3 t/ha to 19.7 t/ha under RCP8.5 by 2100 whereas Yw of yam will decrease from 30.4 t/ha to 20.4 t/ha (Fig. 2).

3.1. Maize

In the period, 1991 to 2014, maize yields in Benin increased at an average rate of 14 kg/ha/year (FAO, 2016). Currently, maize yield gap in Benin is about 80% of Yw. To maintain current levels of per capita maize availability (51 kg/person/year) without cropland expansion, the yield gap would have to be reduced to between 70% and 80% of Yw by 2050 and between 20% and 40% of Yw by 2100 depending on the scenario (Fig. 3). If maize yields continue to grow linearly at the current rate, the yield gap will be between 67% and 72% of Yw by 2050. This would be adequate to maintain current levels of per capita maize availability in all scenarios including scenarios with no cropland expansion. By 2100, however, continued yield increases at the current rate will be inadequate to maintain the current level of maize availability without cropland expansion (Fig. 3). At the current rate of yield growth, maize yield gap is likely to be between 27% and 45% of Yw by 2100 depending on the scenario. This would be inadequate to maintain current levels of per capita maize availability in scenarios with no cropland expansion (Fig. 3). Without the stated levels of yield gap closure on existing production areas by 2100, cropland expansion will be required to maintain current levels of maize availability. Currently, the physical area for maize cultivation in the study area is about 210,000 ha and the harvested area is about 350,000 ha (i.e. cropping intensity of 1.5) (You et al., 2014). Based on the current share of crop areas, about 200,000 ha of physical area outside protected areas is available for maize cultivation. At the current rate of yield increase and with the current cropping intensity of 1.5, these areas in addition to the current maize area will barely be adequate to maintain current level of availability by 2100 in all scenarios.

3.2. Cassava

Currently, the cassava yield gap in Benin is about 50% of Yw and per capita availability is about 137 kg/person/year (FAO, 2016). To maintain

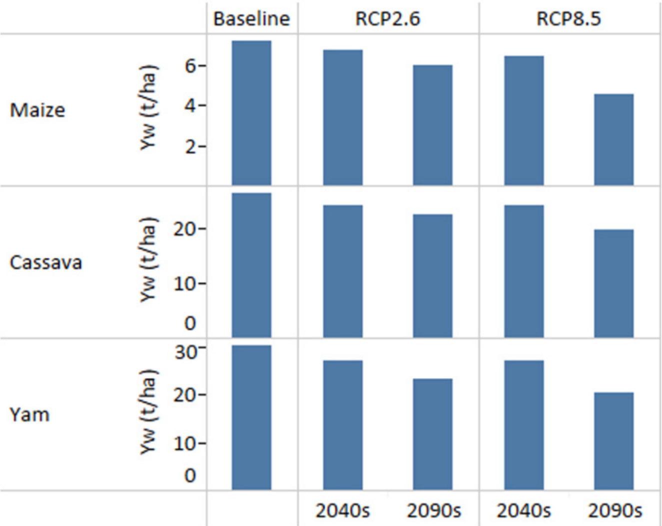

Fig. 2. Water-limited yield potentials (Yw) under different climate change scenarios.

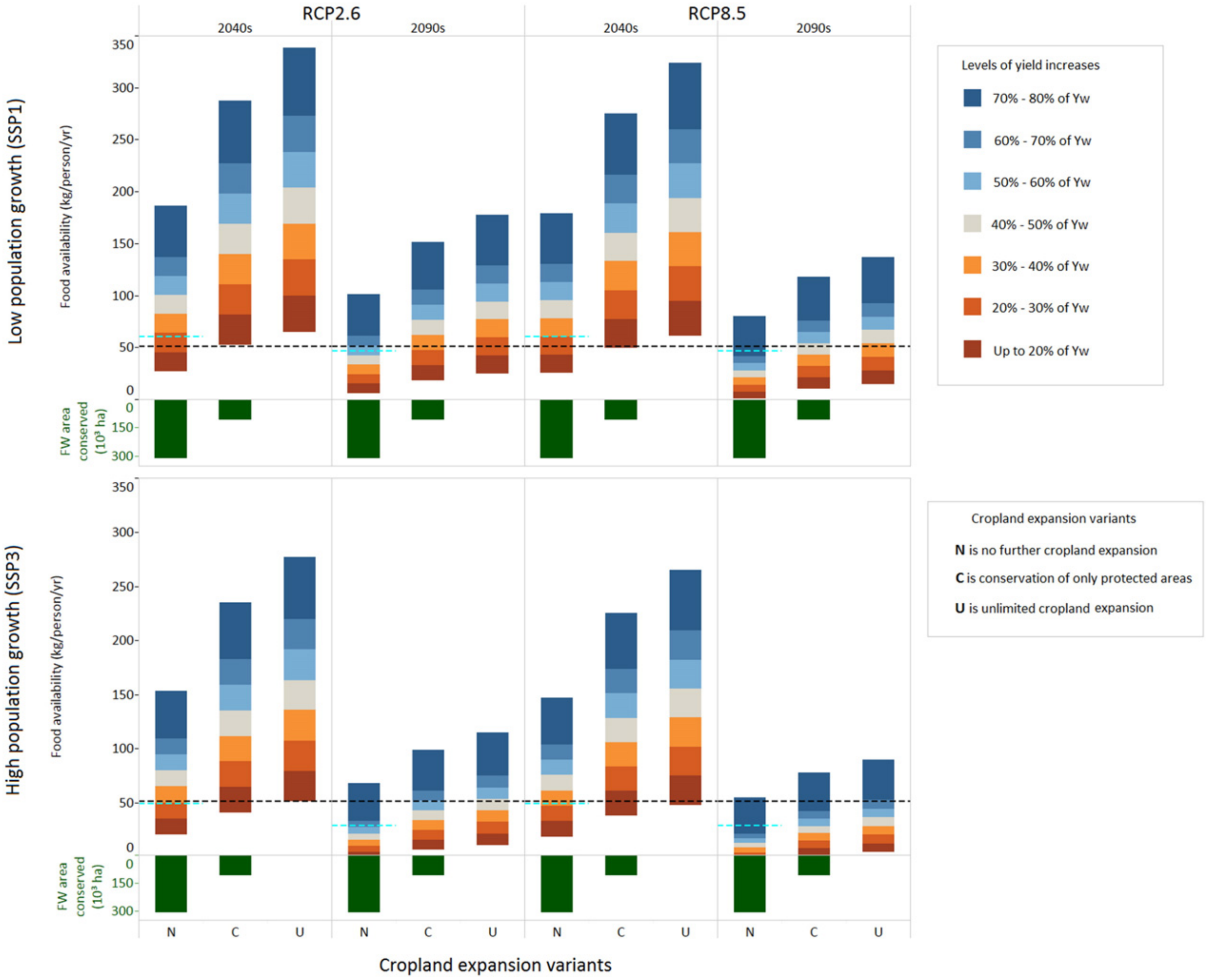

Fig. 3. Trade-offs between per capita maize availability, and forest and woodland conservation under different scenario combinations of climate change, population growth and yield increases. FW is forest and woodland area conserved. Black dashed line indicates availability of food per capita for the baseline period (2001 − 2011). Blue dashed lines indicate per capita food availability based on continuation of trends in maize yields on existing cropland areas (i.e. an increase of 14 kg/ha/year) (FAO, 2016). The current average farmer yield is about 20% of Yw.

the current level of per capita cassava availability without cropland expansion, the yield gap would have to be reduced to between 24% and 32% of Yw by 2050. If cassava yields continue to grow linearly at the current rate of 333 kg/ha/year (FAO, 2016), this would reduce yield gap to 20% of Yw or less depending on the scenario. This would be adequate to maintain per capita cassava availability in all scenarios by 2050 including scenarios with no cropland expansion (Fig. 4). Per capita availability will rise above current levels (between 150 and 180 kg/person/year depending on the scenario). However, by 2100, even cassava yields of 80% of Yw are likely to be inadequate to maintain current levels of availability in scenarios with no cropland expansion. It is generally accepted that 80% of Yw represents an upper limit of attainable yield under rainfed conditions because of diminishing returns and greater inefficiencies from further investments in yield enhancing inputs and labor (Lobell et al., 2009; van Ittersum et al., 2013; van Ittersum et al., 2016). Hence, by 2100, cropland expansion may be required to maintain current levels of availability. Currently, the physical area for cassava cultivation in the study area is about 90,000 ha and the harvested area is about 131,000 ha (i.e. a cropping intensity of 1.5). Based on the current share of crop areas, an additional total physical area of 92,000 ha is available for cassava cultivation of which 55,000 ha lie outside protected areas. The conversion of 92,000 ha for cassava cultivation in addition to continued yield increases at the current rate and cropping intensity of 1.5 will be adequate to maintain current per capita availability by 2100 only if the population grows at not >1.3% per annum (SSP1). If the population grows at 3% per annum (SSP3), this would be inadequate.

3.3. Yam

Yam yields in Benin increased at an average rate of 160 kg/ha/year in the period 1991–2014 and the current yield gap is about 50% of Yw (FAO, 2016). To maintain the current level of per capita availability (134 kg/person/year) without cropland expansion, the yield gap would have to be reduced to between 20% and 25% of Yw by 2050. At the current rate of yam yield increases, the yield gap will be about 24% of Yw by 2050 in all scenarios. If the population grows at 1.3% per annum (SSP1), the projected levels of yield gap closure would be adequate to maintain current levels of per capita yam availability without cropland expansion (Fig. 5). However, if population grows at 3% per annum (SSP3) then the projected levels of yield gap closure would be inadequate to maintain availability without cropland expansion. By 2100, reducing the yield gap to 20% of Yw (i.e. achieving the upper limit of attainable yields in rainfed conditions) in all scenarios is likely to be inadequate to maintain the current level of per capita yam availability. In such cases, cropland expansion may be required to maintain current level of availability. Based on the current share of areas of crops, a maximum area of 140,000 ha outside protected areas can be converted for yam cultivation. In addition to the current harvested

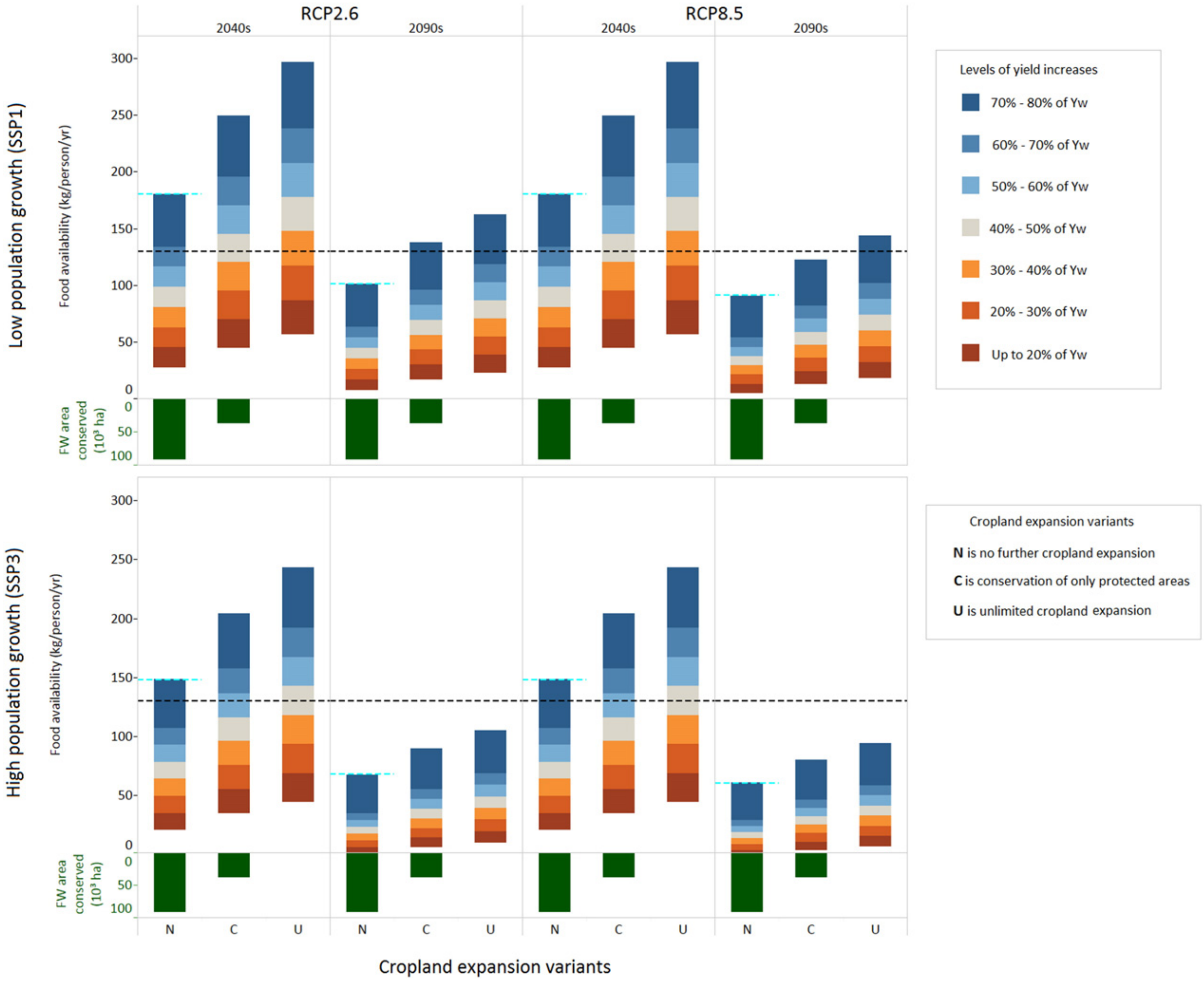

Fig. 4. Trade-offs between per capita cassava availability, and forest and woodland conservation under different scenario combinations of climate change, population growth and yield increases. FW is forest and woodland area conserved. Black dashed line indicates availability for the baseline period (2001–2011). Blue dashed lines indicate per capita food availability based on continuation of trends in cassava yields in existing cropland areas (i.e. an increase of 333 kg/ha/year) (FAO, 2016). The current average farmer yield is about 50% of Yw. For all time-periods, extrapolated yields were higher than Yw and hence Yw were used.

area of 80,000 ha, this will be adequate to maintain current per capita yam availability by 2050 and 2100 in all scenarios.

4. Discussion

The degree of success of intensification measures (such as yield gap closure and increasing cropping intensity) and consequently the level of cropland expansion required to meet food security objectives in Benin will depend on population growth and climate change. Our study shows that substantial levels of yield gap closures are required to maintain current levels of per capita food availability on existing croplands. In most of the scenarios, the required levels of yield gap closures can be achieved by 2050 by maintaining the average rate of yield increases recorded over the past two and half decades. However, yields will have to increase at a faster rate than has been recorded over the past two and half decades in order to achieve the required levels of yield gap closures by 2100. Particularly for yam and maize, the average rate of yield increases recorded over the past two and half decades will have to be doubled if population grows at 3% per annum as projected under SSP3. Population growth rate of 3% per annum is not unlikely and is line with the United Nations population projections (UN, 2015). Over the period 1991–2013, population in Benin increased at a rate of 4% per annum (FAO, 2016). To increase yields at the required rates will require major investment in sustainable intensification such as: improvement of farmer knowledge and capacity through the use of farmer field schools and modern information and communication technologies; science and farmer inputs into technologies and practices that combine crops–animals with agro-ecological and agronomic management; engagement with the private sector for supply of goods and services (Pretty et al., 2011). In our study, we assumed no future changes in diets in all scenarios. Future projections of dietary changes are highly uncertain. Nevertheless, we are aware that dietary changes affect food demand and consequently the degree of cropland expansion as well as share of cropland area used for the cultivation of a specific crop. However, in SSA, dietary changes have been shown to have less effect on food demand and consequently cropland expansion than population growth. For example, van Ittersum et al. (2016) showed that in 10 countries in SSA (which comprise 54% of total SSA population), population growth alone accounts for approximately 75% of the projected increases in food demand.

Despite the efforts aimed at increasing yields, the maximum yield that can be attained in rainfed production systems will be affected by climate change. Climate change will impose biophysical limitations on yield increases by reducing Yw. Reduction of Yw will result in lost opportunities to increase crop production through yield increases in rainfed systems. The implication is that regardless of optimal nutrient management, biotic control and the aforementioned measures, maize, cassava and yam yields in rainfed systems cannot exceed 7 t/ha,

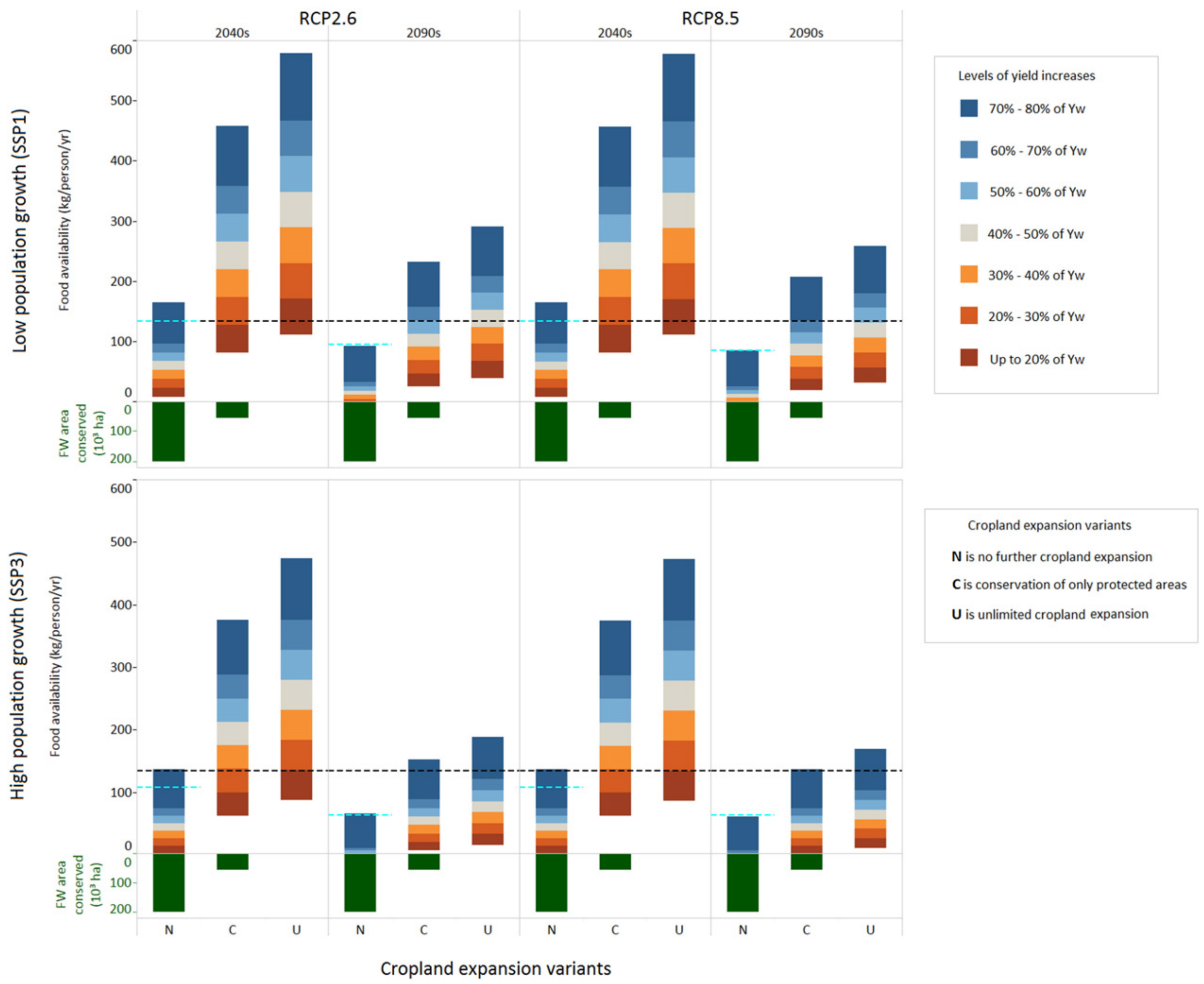

Fig. 5. Trade-offs between per capita yam availability, and forest and woodland conservation under different scenario combinations of climate change, population growth and yield increases. FW is forest and woodland area conserved. Black dashed line indicates availability for the baseline period (2001–2011). Blue dashed lines indicate per capita food availability based on continuation of trends in yam yields in existing cropland areas (i.e. an increase of 160 kg/ha/year) (FAO, 2016). The current average farmer yield is about 50% of Yw. For the 2090s, extrapolated yields were higher than Yw and hence Yw were used.

24 t/ha and 27 t/ha in scenarios with RCP2.6 by 2050. These yields are likely to decrease further in scenarios with RCP8.5 and by 2100. For cassava and maize especially, due to the substantial reduction in Yw, by 2100, attaining 80% of Yw is likely to be inadequate to maintain current levels of food availability in scenarios with no cropland expansion. To a degree, good agronomic practices and irrigation expansion can provide opportunities to overcome biophysical yield limitations imposed by climate change. Water-limited yield potentials can be raised by introducing higher-yielding cultivars that may be either drought resistant or have relatively shorter growth duration (Gornall et al., 2010; Hall and Richards, 2013). Increased application of irrigation can also ensure that full yield potentials are realized instead of water-limited yield potentials (van Ittersum et al., 2013).

Increasing cropping intensity as an option to increasing production in existing croplands will also be affected by climate change. Currently, the cropping intensity of maize, cassava and yam in the study area is 1.5, i.e., the harvested area of each crop is 1.5 times larger than physical area set aside for cultivation (You et al., 2014). In another paper, we showed that between 50% (30,000 ha) and 95% (57,000 ha) of existing croplands in the northern part of the study area (with an area of 14,500 km^2) that can support the cultivation of more than one crop in a year will revert to single cropping as a result of climate change (Duku et al., Unpublished results). In the present study, because we assumed that the best lands in terms of soil moisture availability would be used for the cultivation of maize, cassava and yam, the computed cropping intensity of these crops was the same under in all scenarios. The implication is that in the coming decades maintaining or increasing this cropping intensity in existing croplands will be essential for maintaining current levels of food availability. The consequence of a lower cropping intensity is that either yields will have to increase at a much faster rate and/or more cropland expansion will be required than estimated in this study. Increasing cropping intensity in SSA has been challenging in the past and has been constrained by factors such as high labor intensity, lack of knowledge and lack of market access in addition to length of growing period (Waha et al., 2013). In the coming decades these factors must be addressed and the aforementioned lessons drawn from successful intensification projects in SSA will be useful (Pretty et al., 2011).

Our results show that, as a result of population growth and the impact of climate change, it is likely that forested and woodland savannah areas will be increasingly under pressure in the coming decades in Benin. This may cause tensions between pastoralists traditionally using the areas for grazing and new settlers. Particularly during the dry season, pastoral communities from other parts of Benin and neighbouring countries such as Nigeria often migrate to this study area for grazing (Judex and Thamm, 2008). Furthermore, if there is no change in shares of areas of different crops then our analyses show that in some scenarios the maximum area for cultivation of maize and cassava that is outside protected forests will be inadequate to maintain current levels of food availability. State-owned protected forests in the study area are therefore likely to come under increasing pressure from surrounding villages and migrants from the southern part of Benin looking for land to farm. These protected forests have remained largely intact in recent decades. Apart from the loss of biodiversity and ecosystem services, deforestation and forest degradation also has direct negative impacts on irrigation opportunities (Duku et al., 2016). In another paper, we showed that even if there is no change in forest and woodland cover in the northern part of the study area, at least 50% of irrigation potential will be lost in the coming decades as a result of climate change (Duku et al., Unpublished results). Changes in forest and woodland cover are likely to reduce irrigation potential by as much as 20,000 ha i.e. 80% of the total irrigation potential in the northern part of the study area (Duku et al., 2016). If irrigation expansion will play a crucial role in this study area, then a certain threshold of forest and woodland extent especially in the northern and central parts will be needed to regulate water flows and increase dry season streamflow.

5. Conclusion

Food security in the coming decades will be a major challenge in SSA and our study has shown that efforts to address this will be further challenged by climate change, rapid population growth and the need to protect natural ecosystems such as forests and woodlands. Whereas crop production on existing croplands will have to increase in order to maintain current levels of per capita food availability due to rapid population growth, climate change will reduce the maximum yields that can be attained in existing rainfed production systems. Therefore, substantial levels of yield gap closure will be required to maintain current levels of per capita food availability on existing croplands. In most of the scenarios, the required levels of yield gap closures can be achieved by 2050 by maintaining the average rate of yield increases recorded over the past two and half decades. However, yields will have to increase at a faster rate than has been recorded over the past two and half decades in order to achieve the required levels of yield gap closures by 2100. Particularly for yam and maize, the average rate of yield increases recorded over the past two and half decades will have to be doubled if population grows at 3% per annum as projected under SSP3. Major investments in higher-yielding cultivars and irrigation will be required to raise the yield ceiling in order to overcome the biophysical limitations on further yield growth imposed by climate change. Nevertheless, it is likely that forests and woodlands will come under increasing pressure from cropland expansion in order to make up for lost opportunities to increase production. Without the stated levels of yield gap closure on existing production areas, the areas under maize, cassava and yam cultivation will have to increase by 95%, 100% and 250% respectively in order to maintain the current levels of per capita food availability. Such land conversion should consider the feedback effect of forest and woodland loss on water availability for irrigation (see also Duku et al. (2016)). Our study shows that food security outcomes and forest and woodland conservation goals in Benin and likely the larger SSA region are inextricably linked together and require holistic management strategies that considers trade-offs and co-benefits.

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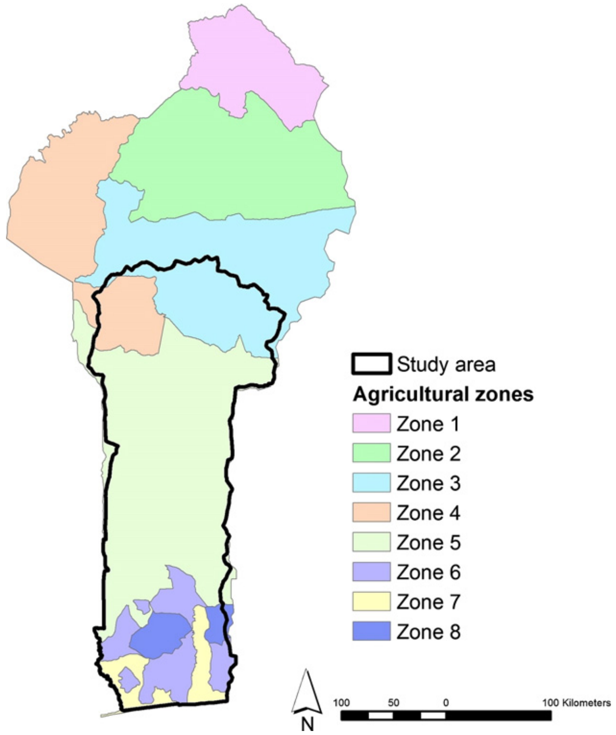
Appendix 1. Delineated agricultural zones of our study area and Benin in general



Appendix 2. General Circulation Models used in this study

General Circulation Model	Institution
BCC-CSM 1.1	Beijing Climate Center, China Meteorological Administration
BCC-CSM 1.1(m)	Beijing Climate Center, China Meteorological Administration
CSIRO-Mk3.6.0	Commonwealth Scientific and Industrial Research Organisation and the Queensland Climate Change Centre of Excellence
FIO-ESM	The First Institute of Oceanography, SOA, China
GFDL-CM3	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2G	Geophysical Fluid Dynamics Laboratory
GFDL-ESM2M	Geophysical Fluid Dynamics Laboratory
GISS-E2-H	NASA Goddard Institute for Space Studies
GISS-E2-R	NASA Goddard Institute for Space Studies
HadGEM2-ES	Met Office Hadley Centre
IPSL-CM5A-LR	Institut Pierre-Simon Laplace
IPSL-CM5A-MR	Institut Pierre-Simon Laplace
MIROC-ESM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC-ESM-CHEM	Atmosphere and Ocean Research Institute (The University of Tokyo), National Institute for Environmental Studies, and Japan Agency for Marine-Earth Science and Technology
MIROC5	Japan Agency for Marine-Earth Science and Technology, Atmosphere and Ocean Research Institute (The University of Tokyo), and National Institute for Environmental Studies
MRI-CGCM3	Meteorological Research Institute
NorESM1-M	Norwegian Climate Centre

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