Simulating the potential impact of deforestation and forest regeneration on crop yield in West Africa

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ABSTRACT

This study examines the potential impacts of deforestation and reforestation on climate and crop yields in West Africa. It combined regional climate and crop yield models to perform a series of multi-year climate and crop yield simulations for West Africa. The simulations used three different land-cover patterns to designate present-day, deforestation, and forest regeneration conditions in the region. The climate model reproduces the essential features of West African climate. The crop model replicates the inter-annual variability of the crop (maize, millet, cowpea and groundnut) yields, and shows how changes in rainfall affect crop yields. The study revealed that the ongoing deforestation along the Guinea zone (4°N –9°N) may reduce West African rainfall by 20%, through reduction in both evapotranspiration and Moisture Flux Convergence (MFC). A 20% drop in rainfall could reduce groundnut yield by 8%, maize yield by 9%, millet yield by 10%, and cowpea yield by 15%. On the other hand, a well-planned forest regeneration in West Africa could increase rainfall by more than 23%. This may increase maize yield by 1%, groundnut yield by 6%, millet yield by 11% and cowpea yield by 19%. These results suggest that integrating trees into agricultural and urban landscapes may assist in mitigating the impact of global warming on West African climate, and can also have positive impact on food production.

Keywords: Rainfall; climate-crop models; crop yields; deforestation; climate change; food production; West Africa

INTRODUCTION

The high rate of deforestation in West Africa remains a serious problem that threatens agricultural productivity and food security in the region. The band of West African forests that once extended from Guinea to Cameroon is virtually gone. Deforestation has been most severe in Nigeria (FAO, 2009), where more than 410,000 hectares of forest are lost to deforestation and forest degradation annually. The annual deforestation rate has increased from 2.7 % of the country land from 1990-2000 to 3.3% between 2000 and 2005; and currently, less than 12.2 % of the country land is forested (FAO, 2006). Between 2000 and 2005, Ghana lost an average of 115,000 hectares of forest per year, which amount to 2.0% of the country land. In general, between 1990 and 2005, West Africa has lost almost 12 million hectares (two times the size of Togo) of tropical forest (FAO, 2006; 2009) with an annual deforestation rate of 1.17% of the total land per annum. Even though, the West African forests constitute only 16% of the world’s total, deforestation rate in Africa is more than six times the world’s average (FAO, 2009).

Evidence exists that deforestation could negatively impact the climate and agriculture of West Africa in future (Roudier et al., 2011; Oguntunde et al., 2013). Deforestation increases the amount of CO2 in the atmosphere, because when forest (which acts as major carbon store) are cleared and the trees are either burnt or rot, the stored carbon is released as CO2 into the atmosphere (Houghton, 2005; Stern, 2006). This in turn causes dangerous greenhouse effect. Deforestation also removes the vegetative cover that absorbs shortwave radiation, thereby, leading to global warming (Gisladottir and Stocking, 2005). Abiodun et al. (2008) showed how extreme deforestation in West Africa increases temperature and decreases rainfall, thereby producing drought, over the entire region. In addition, deforestation leads to land degradation, including depletion of soil nutrients and soil erosion. All these impacts would decrease the productive capacity of land in the region, thereby reducing crops’ potential yields, and consequently lead to food insecurity. Given the potential negative impacts of deforestation, governments of West African countries have been designing strategies and policies to address the problem as part of their poverty reduction and environmental conservation efforts.

Forest encroachment has been the main cause of deforestation in West Africa. People cut down trees to expand cities, build houses, make furniture, create large-scale agriculture, mining of minerals, etc. However, a long-term development entails much more than exploiting the natural resources of the region. A sustainable development should integrate livelihood, climate adaptation and mitigation initiatives with urbanization and agriculture. Hence, forest regeneration (artificial and natural) should be a key component of such a development. Integrating trees into agricultural and urban landscapes is expected to have positive effects on the environment. Apart from creating an effective carbon sink, forest regeneration (e.g. reforestation) would provide a more favourable climate to enhance food production, at the same time, help to adapt to climate change. Therefore, as part of sustainable development, there should be concerted effort towards forest regeneration. Such effort would include
assessing how forest regeneration would improve the climate and agricultural outputs over the region; which is part of motivation for the present study.

Previous studies have reported possible impact of deforestation and/or desertification on the climate of West Africa. For example, Zheng and Eltahir (1998) reported that the West African monsoon circulation and rainfall variability are more sensitive to deforestation than to desertification in contrast to Clark et al. (2001), who from a series of Global Circulation Model (GCM) simulations, reported that desertification has a greater impact on the West African rainfall variability compared to deforestation. However, Taylor et al. (2002) observed a weak response of the monsoon rainfall to land cover changes of realistic magnitude. Abiodun et al. (2008) applied a regional climate model (RegCM3) to study the impact of deforestation and desertification on the monsoon system and suggested that the ongoing desertification and deforestation in West Africa may be major contributors to the persistence of the observed drought over the region. However, how these impacts would affect crop production and food security over the region is not well known.

Therefore, the main purpose of this study was to assess the potential impacts of deforestation and forest regeneration on climate and crop production in West Africa. To achieve this, the study combined a dynamic regional climate model with an empirical crop model to simulate the climate and crop yields in West Africa, using three different land-cover patterns, namely: the present-day, an extreme deforestation, and a well-planned forest regeneration patterns.

**METHODOLOGY**

**Regional Climate Model and Simulations**

The climate model used for the study is the International Centre for Theoretical Physics (ICTP) Regional Climate Model version 3 (RegCM3), described in Pal et al. (2007). RegCM3 uses radiative transfer scheme (Kiehl et al., 1996), Biosphere-Atmosphere Transfer Scheme (BATS; Dickinson et al.,1993), counter gradient planetary boundary layer (PBL; Holtslag et al., 1990), sub-grid explicit and cloud scheme (SUBEX, Pal et al., 2000) and mass flux based cumulus convection scheme (Grell, 1993), with Fritsch and Chappell (1980) closure. The model domain used for the study is similar to that used by Abiodun et al. (2008). Horizontally, the domain extends from 24°S to 38° N and 26°W to 37° E with horizontal grid spacing of 90 km; and vertically, it extends from the surface to 70 hPa with 14 vertical grid points. This large domain is chosen to fully capture the primary features that control the annual cycle of the West African monsoon and to minimize inconsistencies between boundary conditions and the model. However, our study focused on West African region, which extends from 5°S to 30°N and 20°W to 20°E (Figure 1).

Three numerical simulations/experiments were performed. These three simulations used the same model set-up, but different landuse patterns as shown in Figure 1. The first simulation (hereafter, PRS) used the “present-day” vegetation (Figure 1a) as characterized by the United States Geological Survey (USGS) Global Land Cover Characterization (GLCC) version 2 data. The second simulation (hereafter, DEF) was designed to generate the worst-case scenario for deforestation over West Africa; so in the land-cover pattern, forests and tall grasses were replaced with short grasses (Figure 1b). The third simulation (hereafter, REF) was to produce the best-case scenario for forest regeneration over the region by using the potential land-cover (vegetation) over West Africa (Figure 1c) proposed by Adams et al. (1998). This pattern depicts the state of West African land-cover before the onset of the ongoing deforestation. The simulation period was from 1979 to 1990. Data for initial and boundary conditions were taken from the U.S. National Centers for Environmental Prediction - Department of Energy (NCEP-DOE) Reanalysis data (Kalnay et al., 1996) and the U.S. National Ocean and Atmosphere Administration Optimum Interpolation Sea Surface Temperature weekly data (Reynolds et al., 2002).

**Crop Model and Simulations**

The study adopted the empirical crop model developed by Adejuwon (2006) to simulate crop yields. The model employs series of multiple regression equations to compute the annual yield of crops (maize, millet, cowpea, and groundnut) with separate equation for each crop. Using monthly rainfall during the growing season across a station as input, the model simulated the annual crop yield across the station. Crop models were applied over each grid point of the study domain (i.e. West Africa, Figure 1) and used the simulated monthly rainfall at each grid as inputs in producing the corresponding annual crop yields at the grid. This was repeated for the three experiments (PRS, DEF and REF). To account for differences in growing season across the study domain, we used monthly rainfall from June to September for the Sahel region, and from April to July for the Guinea region. The main limitation with this crop model is that it uses only rainfall as input data and thus may not directly account for the influence of other climate and soil variables on crop growth and yield. But, it may indirectly account for the influence of some variables (like soil moisture and relative humidity) that varies with rainfall. To access the impact of deforestation and forest regeneration on climate and crop yield, values of simulated variables in PRS were subtracted from those of DEF and REF, respectively.
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Figure 1: The distribution of the land-cover types in West Africa used for the study: (a) Present-day (PRS), (b) Deforestation (DEF) and (c) Reforestation (REF; the Potential Vegetation) experiments. The land cover types are: (1) disturbed forest, (2) evergreen broadleaf, i.e. tropical forest, (3) tall grass i.e. woodland savannah, (4) short grass, (5) swamp, (6) semi-desert, (7) desert, and (8) crop/mixed farming.

RESULTS AND DISCUSSION

Model Validation

The performance of RegCM3 over West Africa was validated by comparing the model simulations with the observed data. Here, the simulated temperature and rainfall in PRS simulation are compared with the observed data (Figures 2 and 3). In general, the model replicates the essential features of West African climate. The simulated maximum temperature belt lies in the Sahel zone and the minimum is located along the coastal zone in agreement with CRU data (Figure 2). Similar to the observed, the rainfall maximum values are located to the south-west and south-east of the region and the rainfall values generally decreases toward the north. More importantly, the model reproduced the seasonal cycle of the monsoon system, and adequately captured the monthly variation of both temperature and rainfall over the entire West Africa (Figure 3).

Figure 2: Observed and simulated annual mean temperature (Temp; oC) and rainfall (mm day-1).
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Figure 3: Observed and simulated seasonal variation of temperature (Temp; °C) and rainfall over West Africa, averaged over the boxed domain (0-15°N, 15°W-15°E) shown in figure 2(a).

In agreement with observation, the simulated rainfall peak was in August and the lowest in January. Minimum temperatures were in the dry season (January and February), while maximum temperatures occurred during the dry-wet (April) and wet-dry (October) transition months. Interestingly, the model replicates the local temperature minimum in July and August, the months with maximum amount of cloudiness. Nevertheless, RegCM3 exhibits some biases in both temperature and rainfall fields. Figure 3 shows an overestimation of rainfall in the Guinean zone by about 4 mm day⁻¹ (50%), particularly around mountainous areas, and underestimated rainfall over the Sahel by about 2 mm day⁻¹ (50%). The model also shows a cold bias of about 2 °C over the coastal region. The maximum error in rainfall (-2 mm/day) occurred in October, while the maximum error in temperature (-2 °C) was noted in April. These errors are within those reported in previous similar studies in West African (Jenkins, 1997; Afiesimama et al., 2006; Omotosho and Abiodun, 2007; Abiodun et al., 2008). Nevertheless the current simulation adequately captured the all essential climate features needed for this study.

The results of the crop model were also evaluated by comparing the simulated crop yields in PRS with available crop yield data. The simulated yield of different crops exhibited a similar pattern with the annual rainfall (Figure 4). Maize, cowpea and millet yields have maximum values along the coast, while groundnut yield had maximum values between 8°-10°N. It is difficult to holistically validate these results with observation for some reasons.

Firstly, the observed crop yield data to be used to validate the simulation results, are very scarce; such data are not easily accessible and/or available in West Africa. Secondly, in reality, the entire West African region is not cultivated with the crops as simulated here; so what the model simulates is the potential crop yields over the region. The distribution may be different from that of actual yields. Thirdly, even if the entire West Africa were to be cultivated with the crops as the...
model simulated, the distribution of the observed yields may still be different from the simulated (Figure 4), because the present crop model does not include all climate and soil variables that influence crop yields in the simulation. Nevertheless, the objective of our validation here was not to ascertain that model accurately simulated the spatial distribution of crop yield over the region, but to ensure that it reasonably reproduce the inter-annual variability in the yields, as imposed by climate variability.

Figure 5 compares the simulated inter-annual variability of the yields over a station (Potiskum) in West Africa. The observed yield data were obtained from Adejuwon (2006).

Impact of Deforestation

The impacts of deforestation on temperature, rainfall, evapotranspiration and moisture flux convergence (MFC) are shown in Figures 6(a-d). With the deforestation (DEF), temperature increases over the entire West Africa (Fig. 6a). On the average, it increased by 0.6 °C (about 2.1%; Table 1). Deforestation increases temperature because it makes the soil drier (i.e. reduces the soil moisture, Table 1). A drier soil would partition less of the incoming net radiation for latent heating (less evapotranspiration; Fig. 6c) and more for sensible heating (higher temperature). The maximum increase of about 0.7 °C occurred at the centre of West Africa (where short grasses replace tall grasses) and about 1.0 °C occurred to the south-west (where short grasses replaced the evergreen forests) and to the north-east (Fig. 6a). The minimum increase lies along the coastal zones, where the effect of ocean breeze moderates the temperature. In general, the temperature increase occurs in all the months leading to an increase of about 1.2 °C in peak temperature during April and October (Figure 7).
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Figure 6: Simulated changes in temperature (°C), rainfall (mm day⁻¹), evapotranspiration (mm day⁻¹), and moisture flux convergence (MFC; mm day⁻¹) due to the deforestation.

Table 1: Comparison of impacts of deforestation and reforestation on climate and crop yields in West Africa.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Mean value in PRS</th>
<th>Changes due to DEF (%)</th>
<th>Changes due to REF (%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rain (mm/day)</td>
<td>3.6</td>
<td>-20.2</td>
<td>23.2</td>
</tr>
<tr>
<td>Temperature (°C)</td>
<td>26.4</td>
<td>2.1</td>
<td>-0.9</td>
</tr>
<tr>
<td>Evapotranspiration (mm/day)</td>
<td>2.2</td>
<td>-19.8</td>
<td>8.6</td>
</tr>
<tr>
<td>Moisture Flux Convergence</td>
<td>19.6</td>
<td>-7.6</td>
<td>11.0</td>
</tr>
<tr>
<td>Soil moisture (mm)</td>
<td>19.6</td>
<td>-7.6</td>
<td>11.0</td>
</tr>
<tr>
<td>Maize (tonnes/ha)</td>
<td>0.87</td>
<td>-8.6</td>
<td>1.7</td>
</tr>
<tr>
<td>Millet (tonnes/ha)</td>
<td>1.04</td>
<td>-10.2</td>
<td>11.9</td>
</tr>
<tr>
<td>Cowpea (tonnes/ha)</td>
<td>0.52</td>
<td>-15.3</td>
<td>19.6</td>
</tr>
<tr>
<td>Groundnut (tonnes/ha)</td>
<td>1.09</td>
<td>-8.0</td>
<td>6.5</td>
</tr>
</tbody>
</table>

PRS - present day; DEF - deforestation; REF - reforestation
However, temperature increases can have both positive and negative effects on crop yields, depending whether the optimum temperature for the crop growth is exceeded or not. High temperature affects the rate of plant development (vegetative growth) and hence speeds annual crops through the developmental process. It could also increase the frequency and the intensity of heat waves over the region. Heat wave is known to have adverse effect on crop yields in West Africa (Oweis et al., 2000). In addition, temperature increases have been found to reduce yields and quality of many crops. For example, high temperatures shorten the life cycle of grain crops, resulting in a shorter grain filling period, so the plants produce smaller and lighter grains, culminating in lower crop yields and perhaps poorer grain quality (Wolfe, 1995; Adams et al., 1998). This is because temperature increases are associated with higher respiration rates, shorter periods of seed formation and consequently lower biomass production (Molua and Lambi, 2006). Rosenzweig et al. (1993) reported positive crop yield responses to temperature increases of 2 °C but yield reductions were observed at a 4 °C increase. They also found that crop impacts in lower latitudes tend to be more negative than crop impacts in higher latitudes, particularly with respect to wheat and maize yields.

Furthermore, deforestation decreases rainfall over the region. The maximum decrease (about 1.5 mm day⁻¹) occurred in the Guinea zone, while the minimum decrease occurred in the Sahel zone. On the average, deforestation reduced rainfall by 0.7 mm/day (about 20%). The decrease in rainfall can be attributed to a decrease in both evapotranspiration and moisture flux convergence (MFC; Figure 6d). Abiodun et al. (2008) explained how deforestation, due to its frictional effect on monsoon flow and moisture transport, reduces MFC over the Guinea zone. Consistent with Abiodun et al. (2008), the contribution of the MFC to the decrease in rainfall is limited to south of 10°N while that of evapotranspiration extends up to 14°N. But, in contrast to Abiodun et al. (2008), the decrease in rainfall was dominated by the decrease in evapotranspiration. Notwithstanding, this study agrees with the previous studies (Afiesimama et al., 2006; Abiodun et al., 2008; Omotosho and Abiodun, 2007), that deforestation decreases rainfall in West Africa, due to its dynamical and local influence on the rain-producing systems over the region. The decrease in rainfall occurred every month (Figure 7), which may lead to late onset and early cessation of rainfall thereby producing a shorter rainy (or growing) season over the region.

The decrease in annual rainfall caused by deforestation tends to reduce the annual crop yields (Figure 6). The locations of maximum decreases (positioned over Cote D'Ivoire, Nigeria and Cameroon) roughly coincide with those of maximum annual rainfall. Cowpea yield showed the highest deficit (15%) while groundnut yield showed the lowest (8.0%); whereas maize and millet reduced by 8.6% and 10.2%, respectively. It is possible for the crop model to overestimate or underestimate the reduction in the crop yields, because the model does not account for the effect of the increase in temperature from the deforestation. However, our simulated decrease in crop yield due to deforestation is consistent with the findings of Ehui and Hertel (1992) in their studies. They reported that a 10% increase in cumulative deforestation resulted in a 26.9% decrease in aggregate crop yields. Since deforestation decreases the rainfall in all the month, the negative impacts could be due to inadequate rainfall during the growing season or shorter rainfall season, or both. A shorter rainy season could lead to early termination of the growing season, which could have a severe water stress impact on late season crops like cowpea. Cowpea was found to be very sensitive to variations in September rainfall over Sahel (Adejumo, 2006), and was mostly affected by deforestation in this study.

Figure 7: Simulated changes (%) in maize, millet, cowpea, and groundnut yields due the deforestation.
Water supply is usually the most critical factor determining yield. The effects of water shortages on production may vary according to crop type, soil characteristics, root system, and severity and timing of shortages during the growth cycle (Ahn, 1993). Rainfall, a source of soil moisture to crops, is an important variable under rain-fed agriculture mainly practiced in West Africa. In most parts of sub-Saharan Africa, agricultural production is constrained by reduced soil moisture, e.g. in the West African Sahel and parts of southern Africa. Because water availability limits plant growth, further drying would reduce plant productivity (Glantz, 1996). The occurrence of moisture stress during flowering, pollination and grain filling is harmful to crops, particularly to maize, soybean and wheat (Feddema and Freire, 2001; Nicholson, 2001).

**Impact of Forest Regeneration**

The impacts of forest regeneration on temperature, rainfall, evapotranspiration and moisture flux convergence (MFC) are shown in Figures 8(a-d) while a comparison of the impacts of deforestation and reforestation on temperature and rainfall across West Africa is presented in Figure 9.

![Figure 8: Simulated impacts of forest regeneration on temperature, rainfall, evapotranspiration, and moisture flux convergence (MFC)](image)

![Figure 9: Comparison of the impacts of deforestation and reforestation on temperature and rainfall West Africa, spatial averaged over the boxed region (0 – 15°N, 15°W-15°E) in Fig. 3(a).](image)

With the reforestation (REF), the annual temperature decreased along the coastal zone (within 10° lat/lon from coast), but increased further inland to the north-east (Figure 8). The decrease in temperature over the coastal region is because, in contrast to deforestation, reforestation allows more of net radiation to be used for latent heating (increasing...
evapotranspiration) and less for the sensible heating (decreasing temperature). The maximum decrease in temperature (about 0.9 °C) occurred over Côte d'Ivoire and Nigeria, where the disturbed forests are replaced with tropical forests. The reason for the increase in the annual temperature to the north-east is not yet clear. However, a further analysis revealed that, in the north-east, the forest regeneration could produce the increase during rainy season and increases it in dry periods. That is, it may reduce the frequency and intensity of heat waves during rainy season and that of cold outbreak in dry season. Generally, over West Africa, reforestation decreases the temperature by 0.9% (0.2 °C) (Table 1), mostly in the rainy months (April-October) with maximum decrease occurring in July (Figure 9).

Reforestation increases rainfall over the entire West Africa. The maximum increase of about 2.5 mm/day occurred over Côte d'Ivoire and south-west Nigeria, where the disturbed forests are replaced with tropical forests (Figure 7). It is evident that the increase in rainfall is mainly due to the increase in MFC, which contributed more than 70% while evapotranspiration contributed less than 30%. Forest regeneration was contributed due to the increase in MFC because it reduced the speed of monsoon flows, causing the moisture of the flow to converge more over the region and this would trigger more deep convective rainfall. However, on the average, reforestation increases the West African rainfall by 23% and the increase occurred every month (Figure 8). This leads to increase in rainfall amount and length of the rainy season. This is expected to have positive impact on agriculture. For instance, it could provide sufficient time to crop twice (i.e. early and late cropping) in the Savanna zone similar to the current practice in the Guinea zone.

The crop model results show that the increase in rainfall (from reforestation) enhances crop yields, but surprisingly, not over the entire West Africa (Figure 10). Millet and cowpea yields improved over regions where the increase in rainfall was more than 0.1 mm/day and reduce elsewhere. Maize and groundnut yields increased over the regions where the rainfall increase was more than 0.5 mm/day and decrease elsewhere. A further analysis, to investigate the cause of the decrease in the crop yield, revealed that, over the Sahel, increase in rain was higher in June and July than in September. Observational study over this region, on which the model was calibrated, showed that maize yield was positively correlated with June, July and September rains, but negatively correlated with addition of June and July rainfall amount. Hence, a strong high increase in June and July rainfall without a corresponding increase in September would make the magnitude of the negative term higher than the positive terms, thereby, producing a negative yield. However, on the average over West Africa, deforestation produced an increase in yield of all the crops (Table 1). Cowpea yield showed the highest increase (19.6%) while maize had the lowest yield (1.7%). Millet and groundnut increased by 11.9% and 6.5%, respectively. Note that values do not account for the influence of temperature. Also, a more complex model could give different values; for instance, with a 20% increase rainfall, a more complex model (EPIC) simulated 4.4% and 1.07% increase in maize and millet, respectively (Adejomo, 2006). All the same, both models agree that a 20% increase in rainfall will produce a significant increase in crop yield over West Africa.

Figure 10: Simulated impacts of reforestation on maize, millet, cowpea, and groundnut yields (tonnes/hectare)
CONCLUSION

This study combined a dynamic regional climate model (RegCM3) with an empirical crop yield model to highlight the potential impacts of an extreme deforestation and a well-planned forest regeneration could have on climate change and crop yields in West Africa. Before using the model we established the suitability of the models in reproducing West African climate and the crop yields variability. Deforestation could reduce the West African rainfall as well as crops (cowpea, millet and maize) yields. On the contrary, forest regeneration could significantly increase rainfall and consequently increase crop yield in the study area. Thus, forest regeneration would not only mitigate the impact of climate change over West Africa, it could enhance the agricultural productivity over the region.

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REFERENCES


