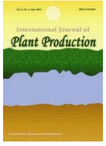

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Impacts of projected changes and variability in climatic data on major food crops yields in Rwanda

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Abstract

This paper investigated the response of major food crop yields namely beans, cassava, Irish potatoes, maize and sweet potatoes to ongoing changes in climate in Rwanda. The projected daily precipitation and temperature data for the period 2000-2050 used in this study were generated by stochastic weather generator (LARS-WG) from daily raw data for the period 1961-2000. These data were collected from Rwandan Meteorological Center based in Kigali, while the agricultural records for the period 2000-2010 used to project yields of major food crops for 2011-2050 were obtained from the National Institute of Statistics of Rwanda and the Ministry of Agriculture and Animal Resources. A number of statistical techniques were applied in projecting the major food crops yields and attempting to quantify their magnitude trends in response to projected precipitation and temperature data. The climate and soil suitability analysis revealed that the central plateau and south-west regions of the country will be the most suitable regions for cultivation of major food crops except Irish potatoes which can be grown in the north-western highlands. The central plateau region is the only region that is expected to experience an increase in yields for most of the major food crops under investigation. The south-west region will have increased beans, cassava and sweet potatoes yields in season A (September-January). The eastern lowlands are expected to register a decreasing trend in most of crops yields in season A, corresponding to the anticipated decline in mean rainfalls and number of rainy days. The envisaged yields increase in season B (February-June) for beans, maize and Irish potatoes will be in response to a rise in mean rainfall and number of rainy days. Heavy rainfall in the north-western region is likely to have a negative impact on crop yields. The rain might cause waterlogging, flooding events and landslides which may damage and destroy the crops.

Keywords: Climate change; Impacts; Crops suitability; Crops yields; Rwanda.

Introduction

Climate change and variability are among the foremost long-term threats to humanity today. The phenomena affect all sectors of life in general and agriculture in particular. Climatic variables (e.g. precipitation, temperatures, sunshine, wind direction and speed, etc.) are some of the key determinants of crop production (FAO, 2008). Lobell and Field (2007) indicated that temperature and precipitation account for approximately 30% of year-to-year variations in global average yields for the world's most widely grown crops. In areas such as the tropical and sub-tropical developing countries where agriculture is rain-fed, coupled with low agricultural inputs (fertilizers, manure, pesticides, etc.), climatic fluctuations account for as much as 80% of variability of production (Hoogenboom, 2000). This could be the case for Rwanda. Changes in temperature, precipitation regimes and patterns impact on the productivity of land, crop growing period, agronomic practices and seed needs. Consequently, crop yields are affected but the impacts are not the same for different crops and climatic regions (Parry et al., 2004).

The significant increase in mean annual temperatures of between 0.036 °C and 0.066 °C per year resulted in a high decline in mean rainfall and number of rainy days and De Martonne aridity index of between 0.12 and 0.36 per year over the areas of Rwanda already having low water supply (e.g. eastern lowlands) may readily accelerate the aridity rate (Muhire and Ahmed, 2014a; Muhire et al., 2014b). Consequently, there may be reduced water for agriculture and the resultant diminished crop production. The non-significant increase in mean annual temperature of between 0.018 °C and 0.03 °C followed by a significant increase in precipitation at a rate of between 2 mm and 6.5 mm per year over the Congo-Nile crest and the northern highlands for the period of 1935-1992 resulted in an increase in De Martonne aridity index of between 0.12 and 0.6 per year for the period of 1961-1992 (Muhire and Ahmed, 2014a; Muhire and Ahmed, 2014b).

It is worth noting that the cases of prolonged droughts followed by famines were registered in Rwanda since the beginning of the last century (Bart, 1993; MINITERE, 2006). However, there is no published data to show the extent of these droughts, the relationships between changes in temperature, rainfall and food security. A conclusion linking famines to drought episodes has been made using common and popular knowledge about climatic conditions. Cases of flooding episodes, soil erosion, landslides caused by heavy rainfall have been observed in the northern (Bulera, Gakenke, Gicumbi, Musanze, Nyabihu and Rulindo Districts) and the western (Karongi, Ngororero, Nyamagabe and Nyamasheke Districts, etc) regions of Rwanda and as well as in other isolated parts of the country especially in 2001, 2002, 2007, 2008 and 2012 (David et al., 2011). The above mentioned cases have not only destroyed the physical environment but also human activities like agriculture. On the other hand, however, there is no published scientific work showing the extent of these flooding episodes and their effects on the economy of the country in general and on agricultural (food crops) production in particular. In addition, the population of Rwanda are less informed about the expected climatic conditions to enable them to assess food crops production responses to projected climate changes and variability and prepare accordingly. It is from the above mentioned motives that this study was conducted to investigate climate change and variability and their impacts on the yields of major food crops in Rwanda.

Hence, it is of paramount importance to make projections on changes in precipitation and temperature so as to define the most suitable crops to cultivate in specific areas, together with their expected productivity. This will also help to design and implement the most suitable measures to deal with ongoing changes in climate with a view to combating food insecurity in developing countries like Rwanda. In as much as edaphic parameter (e.g. soil texture and structure, soil depth, slope gradient and sum of basic cations) and terrain play a role in influencing the variations of agricultural production, they vary less compared to the climatic variables. It is not easy to project their changes with time, as is the case with soil management. A comparison of the crop-specific requirements with land characteristics may be determined to give an idea on the crops to grow (in the coming years) in a given area in response to ongoing changes in climate. However, soil management systems and agronomic practices that are undertaken midway may ultimately change the projections.

It is important to clarify at the outset that there is a strong relationship between precipitation, temperature and the topography of the country (Muhire and Ahmed, 2014a). Precipitation is more intense in the highlands and low in the lowlands. The reverse is true of temperature. Therefore, climatic suitability goes hand in hand with topographic suitability for cultivation of major food crops in Rwanda. A suitable area for cultivation of a given crop is considered as one on which sustained use is expected to yield benefits that will justify the required recurrent inputs without unacceptable risk to land resources on the site and in adjacent areas (Verdoodt and Van Ranst, 2003). It is projected that expected insignificant changes in temperature (minimum, maximum and average) for the period up to 2050 might have little impact on crops productivity if they remain within the threshold limits for crop growth in Rwanda (Muhire et al., 2014). They may, however, heighten the incidences of vectors and pests, which are harmful to crops (FAO, 2008).

Therefore, the aim of this study is to establish crop yields responses to ongoing changes in climate across Rwanda. Such studies are required especially in developing countries like Rwanda, where rain-fed agriculture is the mainstay of the livelihoods of quite a huge chunk of the population.

Area of study

Rwanda is a small landlocked country located in East Africa. It lies between 1° 4´ and 2° 51´ south and 28° 53´and 30° 53´ east and covers an area of 26,338 square kilometres (Sirven et al., 1974; Ilunga et al., 2004; MINERENA, 2011). The country was made up of 11 provinces and Kigali City before the 2006 administrative reforms, which saw it subdivided into 30 districts and five provinces including Kigali City (Figure 1) (REMA, 2009; MINERENA, 2011).

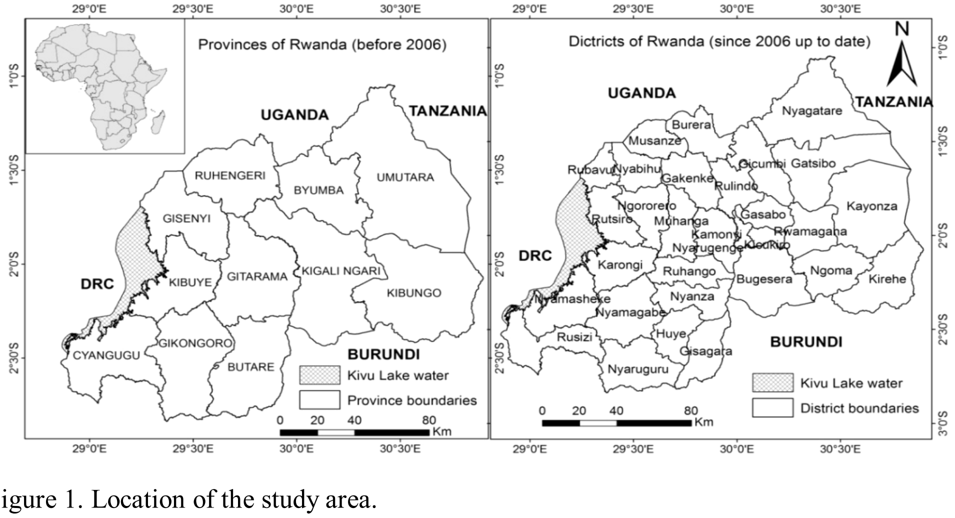

Figure 1. Location of the study area.

Despite its proximity to the equator, Rwanda enjoys a tropical climate that is moderated by hilly topography, varying between 900 m and 4507 m. It stretches from east to west with annual mean rainfall ranging between 750 mm and 1550 mm for 1961-1992. These figures are projected to be in the range of 750 mm and 1650 mm for the period 2011-2050 (Sirven et al., 1974; Ilunga et al., 2004; Muhire and Ahmed, 2014a; Muhire et al., 2014b). Annual mean temperature vary between 22 °C and 16 °C in the eastern lowlands and northern highlands, respectively (Sirven et al., 1974; Ilunga et al., 2004; Muhire and Ahmed, 2014a). However, an insignificant decreasing trend in annual mean temperature is expected for the period 2011-2050 (Muhire et al., 2014b).

Rwanda has four climatic seasons in which the long rainy (March-April-May) and short rainy (September-October-November) seasons alternate with long dry (June-July-August) and short dry (December-January-February) seasons. These seasons are controlled mainly by regional atmospheric circulation and defined based on precipitation patterns and regimes (Sirven et al., 1974; Ilunga et al., 2004; Kizza et al., 2009; Muhire and Ahmed, 2014a). The long and short rainy seasons constitute the crop growing periods for agricultural seasons “B” (February-June) and “A” (September-January of the following year) respectively. Therefore, any change in precipitation patterns and regimes during these seasons affects crops productivity in the country.

It is worth noting that more than 85% of the population of Rwanda is engaged in rain-fed agriculture (NISR, 2011), which is dominantly subsistence and traditional in nature. Notwithstanding that the total arable land of Rwanda is about 14,000 km^2 or 52% of the country’s total surface area, the total cultivated area rose to 1,747,559 hectares (or 66.35% of the country’s total surface area) in 2010 (NISR, 2010 and 2011) with 93,754 hectares (57%) of the 165,000 hectares of marshlands under cultivation throughout the year (REMA, 2009; NISR, 2011). This means in essence that some of the lofty, rugged mountainous and protected areas have progressively been put under agriculture. As such, there could be increased soil erosion, landslides, which lead to soil degradation and subsequent low crops productivity.

Food crops cover about 67.1% of all cultivated farmlands, where multiple cropping systems are practised throughout season “A” (September-January of the following year) and “B” (February-June) respectively (Ilunga et al., 2008; MINAGRI, 2010; NISR, 2011). Farm ownership per household has decreased from 1.2 ha in 1984 to 0.89 ha in 1990 and 0.6 ha in 2010 (Mpyisi et al., 2003; NISR, 2010; NISR, 2011), a reduction of 50% over 16 years owing to high population growth (NISR, 2010; NISR, 2011). The decrease in farm ownership will remain as long as the population growth is high. The small plots are overexploited throughout the year, which leads to more soil degradation and the resultant low crops productivity. The situation, as mentioned earlier, is expected to worsen when climate change and variability impacts come into play.

In addition, it was observed that most of the food crops in Rwanda are not grown in strict adherence to their agro-climatic requirements. The end result is low productivity since they are mostly grown in unsuitable areas. Beans, cassava, Irish potatoes, maize and sweet potatoes (selected for investigation in this study) are grown over large areas in most parts of the country during the two agricultural seasons (A and B). Therefore, they account more than 70% of food crops production in Rwanda as it has been presented by Muhire et al. (2014a).

Materials and Methods

The raw daily precipitation and temperature data used in this study were collected from the Rwandan Meteorological Center based in Kigali. The projected daily data for the period 2000-2050 from which the seasonal and annual mean temperature and precipitation records were generated by stochastic weather generator (LARS-WG) (Racsko et al., 1991; Semenov and Barrow, 1997; Semenov and Brooks, 1999; Muhire et al., 2014b). Notwithstanding the importance of analysing the solar radiation data in projecting the yields of food crops in a given area, this has not been adequately done due to lack of enough representative solar radiation long-term data set.

Agricultural records of total production and cultivated areas from which the yields (kilograms per hectare) of five major food crops (i.e. beans, cassava, Irish potatoes, maize and sweet potatoes) per province and district for the period 2000-2010 were derived. These were obtained from the National Institute of Statistics of Rwanda (NISR) and the Ministry of Agriculture and Animal Resources (MINAGRI). The lack of comprehensive agricultural long-term records (around 30 years) is a slight drawback in projecting food crop yields response to changing climate for long-term periods over Rwanda.

The precipitation, temperature (minimum and maximum) and yields data for the period 2000-2010 were used in building the models. The observed temperature, precipitation and major food crops yields data for this period (2000-2010) were used in validating the models. Precipitation and temperature data for the period 2011-2050 were used in predicting the major food crops yields for the same period. Precipitation and temperature data for the latter period were also used in determining the potential climatic suitability for the cultivation of major food crops in Rwanda. It is worth noting that the growth rainfall, temperature and elevation limits have been fixed based on the optimum climatic and topographic requirements of each crop as have been used by Verdoodt and Van Ranst (2003). In order to project the yields of the above mentioned crops in response to the changing precipitation and temperature for the period 2011-2050, multiple regression analysis was adopted, as it was used by Zemba et al. (2013). The yields were expressed as dependent variables (Y) and climatic indices as independent variables (X). The general form of the multiple regression equation is presented as follows:

$$\mathrm{Y} = \beta_0 + \beta_1 X_1 + \beta_2 X_2 + \beta_3 X_3 + \beta_4 X_4 + \beta_5 X_5 + \beta_6 X_6 + \varepsilon$$

where β_0 is the intercept or constant term, β_k is the change in Y corresponding to one unit increase in X_k when other predictor variables remain constant for $k = 1,2,....,6$ and ε is the error term.

Y = crop (e.g. beans, cassava, Irish potatoes, maize, sweet potatoes) yield in kg/ha

X_1 = maximum temperature in °C

X_2 = minimum temperature in °C

X_3 = Rainfall in February (for season B); in September (for season A)

X_4 = Rainfall in March (for season B); in October (for season A)

X_5 = Rainfall in April (for season B); in November (for season A)

X_6= Rainfall in May (for season B); in December (for season A)

The parameters β_k, $k = 0,1,...,6$ were estimated using the data for the period 2000 to 2010 and then the model used values of the predictor variables (X's) to estimate the yield (Y) for the period 2011-2050. As an example, for the fitted equation for the yield of beans in Cyangugu for season A during the period 2000 to 2010 is given by:

$$Y = 25511.90 - 37.86X_1 - 1482.45X_2 - 0.87X_3 + 2.27X_4 - 0.62X_5 - 2.13X_6$$

This model indicates that yields increases with time (43.09 kg per year when other variables are maintained constant). The yield also increases with October and December rainfalls, but decreases with temperature and September and November rainfalls. However, these conclusions are weakened by the fact that parameter estimates are not significant. A check for multicollinearity between predictor variables indicates that “minimum temperature” and “rainfall in October” are collinear. However, it is known that multicollinearity does not reduce the predictive power of the regression model (Kumar and Krishna, 1975; Kock and Lynn, 2012). Then, similar models were fitted for other crops and other provinces and precipitation, temperature and food crops yields data for the period 2000-2010 were used to validate the models.

Then, a number of statistical techniques were applied to determine the magnitude and direction of yield trends for each crop in every province at seasonal resolutions (A and B), as were also used by Parry et al. (2004); Agustin (2006); Rodrigo and Trigo (2007); Kizza et al. (2009) and Del Río et al. (2012). The linear trend values represented by the slope of the multiple linear regression showed the rise/fall in yield of each crop at provincial level (Jain and Kumar, 2012).

The magnitude of the trends derived from linear regression analysis were calculated (Sene and Farquharson, 1998; Partal and Kahya, 2006; Tonkaz et al., 2007; Peterson et al., 2008; Kizza et al., 2009; Olofintoye and Sule, 2010; Karpouzos et al., 2010; Del Río et al., 2012) using Stata software 13 (StataCorp, 2013; Christopher, 2011). Arc Map 10.1 software (ESRI, 2011) was used to interpolate the climatic suitability of each crop, magnitude and direction of yield trend maps, as has been used by Del Río et al. (2012).

Results and Discussion

Potential climatic and topographic suitability for cultivation of major food crops in Rwanda

The projections revealed that the precipitation data (mean rainfall and number of rainy days) are to vary more compared to temperatures, which are only expected to change slightly in the coming years (up to 2050) (Muhire et al., 2014b). Low temperatures could damage the successful growth of crops in high altitude regions of Rwanda (Verdoodt and Van Ranst, 2003); the projected temperatures are most likely to fall within the threshold limits for good growth of food crops in most parts of the country (Figure 2). Therefore, precipitation and elevation are bound to be the most limiting climatic parameter for cultivation in selected areas of the country (Figure 4).

Despite the fact that the rainfall, temperature and elevation requirements by crops differ from one climatic region to another or one subspecies to another, there are the average rainfall, temperature and elevation required to realise optimum crop growth in a given area (Table 1). The mean precipitations and temperatures during crop growing periods are presented (Figure 3), but it is Table 1 that fully captures the optimum mean annual rainfall, temperature and altitude limits for the different food crops under investigation.

It is estimated that the optimal average rainfall needed to grow the major food crops in Rwanda ranges from 1000 mm to 1200 mm, with a minimum and maximum average of 800 mm and 1500 mm, respectively. These rainfall threshold limits fall within the projected rainfalls and temperatures (Figure 2). Save for the volcanic regions where the annual mean temperatures are below 17 °C, other regions have temperatures ranging between 18 °C and 22 °C.

Although the spatial variations of mean annual temperature for the period 2011-2050 was not done, it was observed that on average, there will be a steady decline in temperature, mean rainfall and frequency of rainfall across the country for the period 2011-2050 compared to the period 1961-2010 (Muhire et al., 2014). An insignificant decrease in temperature is anticipated especially during the rainy seasons, while it is expected to rise during the dry seasons. At annual resolution, a negative trend of between 0.0057 °C and 0.014 °C per decade (minimum and maximum temperatures) is predicted at most referenced weather stations except at Gisenyi and Kamembe, where it is projected to stand at between 0.005 °C and 0.0018 °C per decade, respectively (Muhire et al., 2014b). This shows that the annual mean temperatures are expected to change marginally, which means that it might not have any real impact on cultivation of the crops in Rwanda for the period 2011-2050 (Figure 2).

Save for the short rainy season, a positive trend in mean rainfall is expected over the south-west, the north-east regions and the northern highlands, a phenomenon that will cause an annual mean rainfall of between 1300 mm and 1650 mm for the period 2011-2050. The other regions (central, south-east and western) are likely to experience a decline in mean rainfall, projected to be within the ranges of 775 and 1000 mm (Figure 2).

Table 1. Growth rainfall and elevation limits of the crops investigated in this study.

Crops	Optimal average rainfall (mm)	Maximum average rainfall (mm)	Minimum average rainfall (mm)	Optimum temperature (°C)	Minimum temperature (°C)	Maximum temperature (°C)	Altitude	Harvesting period
Beans	1,000	1200	800	20	18	24	≤2500	Dec-Jan and June-July
Cassava	1,000	1200	800	20	18	24	≤1800	All year
Maize	1,000	1200	800	20	18	24	≤2000	Dec-Jan and June-July
Irish potatoes	1,200	1500	900	18	16	20	≤2000	Dec-Jan and June-July
Sweet potatoes	1,000	1400	800	20	18	24	≤1800	All year

Source: Verdoodt and Van Ranst, 2003.

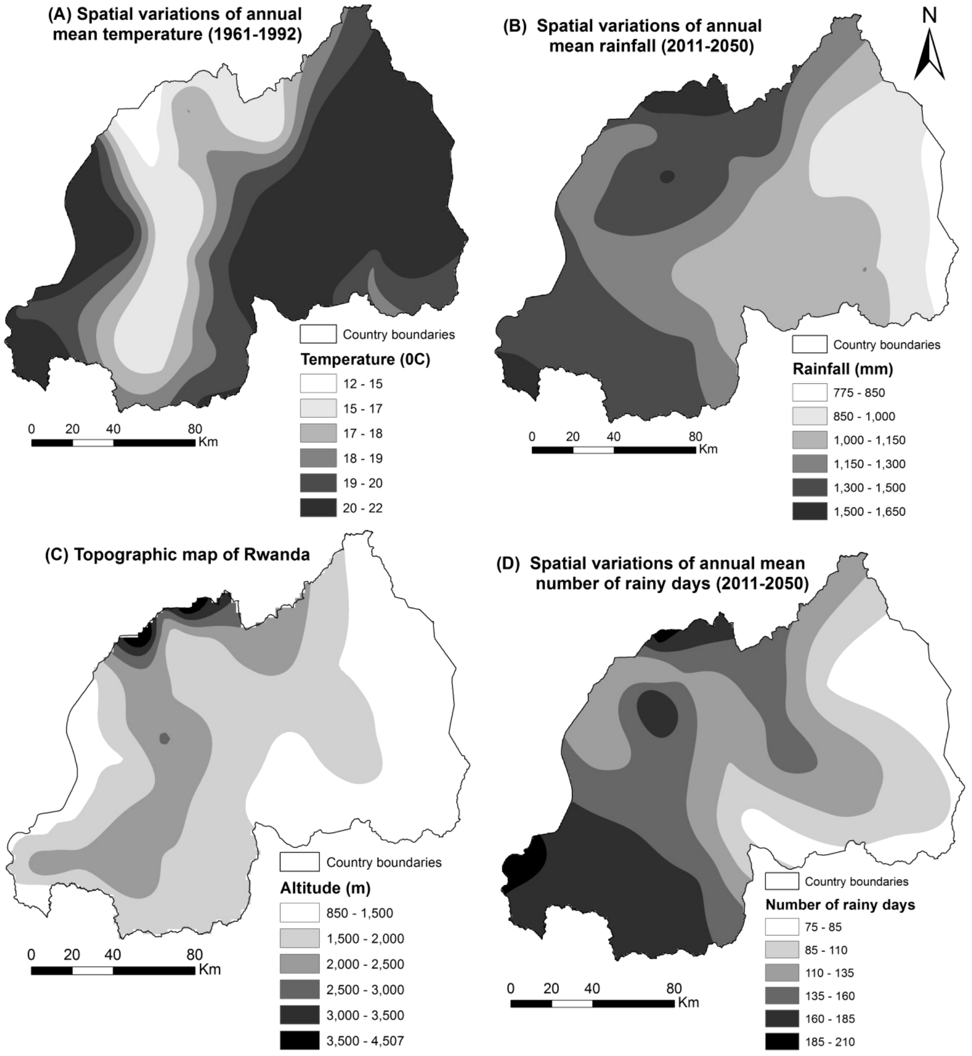

Figure 2. Topography and spatial variations of annual mean temperature and rainfall of Rwanda.

The decline in mean rainfall during the rainy seasons may be a response to predicted decreases in temperature. The number of rainy days (days with rainfall of more than zero mm) will decrease in the central plateau and the south-eastern lowlands (75-110); while the south-west and the north-west regions are expected to have a pattern of increased number of rainy days (160-210), which is almost double that of the former (Figure 3). This translates to an extension of the crop growing periods over the south-west, the north-west and north-east regions and a reduction of the same over the central plateau and the south-eastern lowlands. The mean rainfall and number of rainy days could remain just adequate in the central plateau to support safe growth of major food crops.

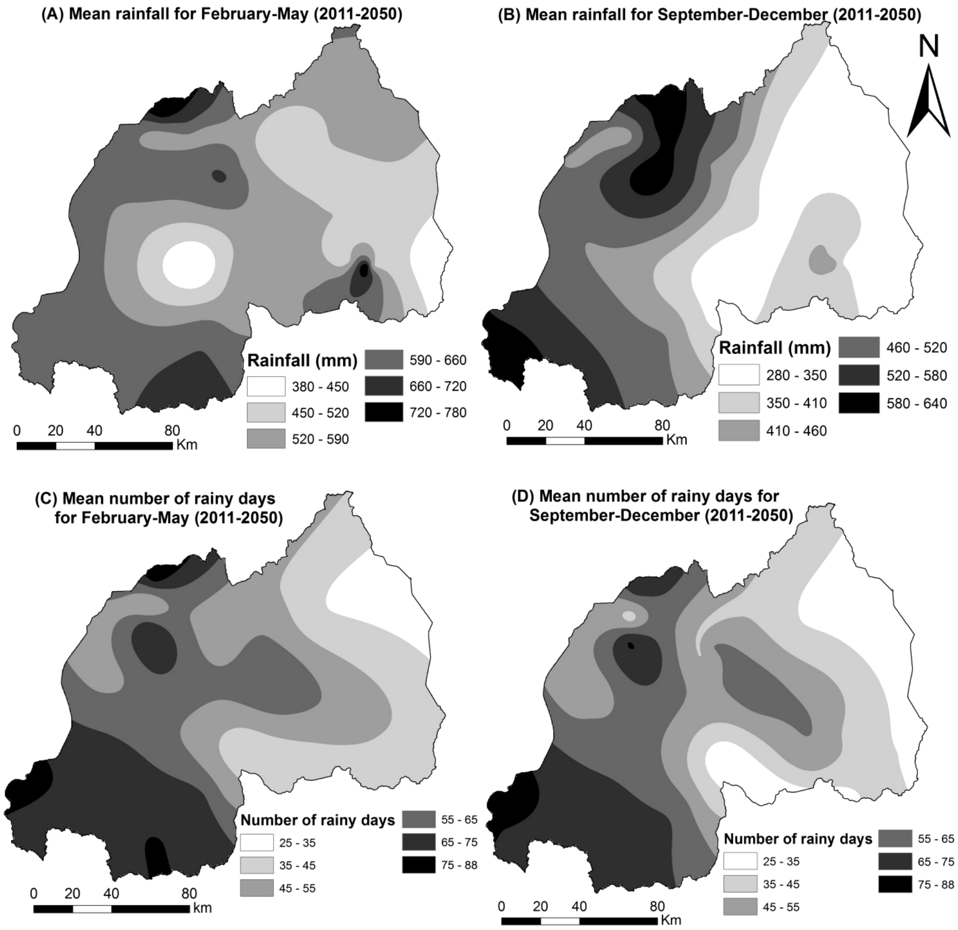

Figure 3. Spatial variations of precipitation data during crop growing periods for 2011-2050.

It is evident from Figures 3 (A) and (B) that the periods February-May and September to December, which correspond to the crop growing periods for seasons "B" and "A" respectively will cumulatively receive around 90% of the annual mean rainfall. The former period will receive around 50% of the annual mean rainfall. It means, therefore, that the central plateau and the south-eastern lowlands will receive an average of around 3 mm of rainfall per day, while it will stand at around 5.8 mm per day over the south-west, the north-west regions during the crop growing period of February-May, and fall slightly to 2.5 mm and 5 mm in September-December. Figures 3 (C) and (D) show that it will be raining at least once in every two days over the south-west and the north-west regions and once in four days over the central plateau and the south-eastern lowlands. The former longer wet spells might easily lead to crop damage from waterlogging, flooding episodes and landslides.

Although the central plateau and eastern lowlands are expected to receive a reduced annual mean rainfall and number of rainy days, these may not significantly lead to reduced crop growing periods and crop productivity especially in season "B". This could result from the observed significant decrease in number of rainy days in May, which is part of the crop growing period for season "B". It is worth noting that while the projection of weather extreme events is not an easy task even in the developed world, it would be helpful to make accurate projections for the coming years. Figure 4 shows the potential climatic and topographic suitability for cultivation of major food crops in Rwanda.

It is evident from Figure 4 above, that only the eastern lowlands have a limited annual mean rainfall water to support the growth of major food crops. The altitudinal elevation of Rwanda is the most challenging factor for agriculture especially in the north-western highlands and the Congo-Nile crest. The central plateau is best suited for the cultivation of the major food crops, except Irish potatoes, which do well in the north-western highlands. The potential soil suitability analysis for cultivation of these crops has been done in an effort to offer more accurate information for delimiting the most suitable areas to grow specific crops.

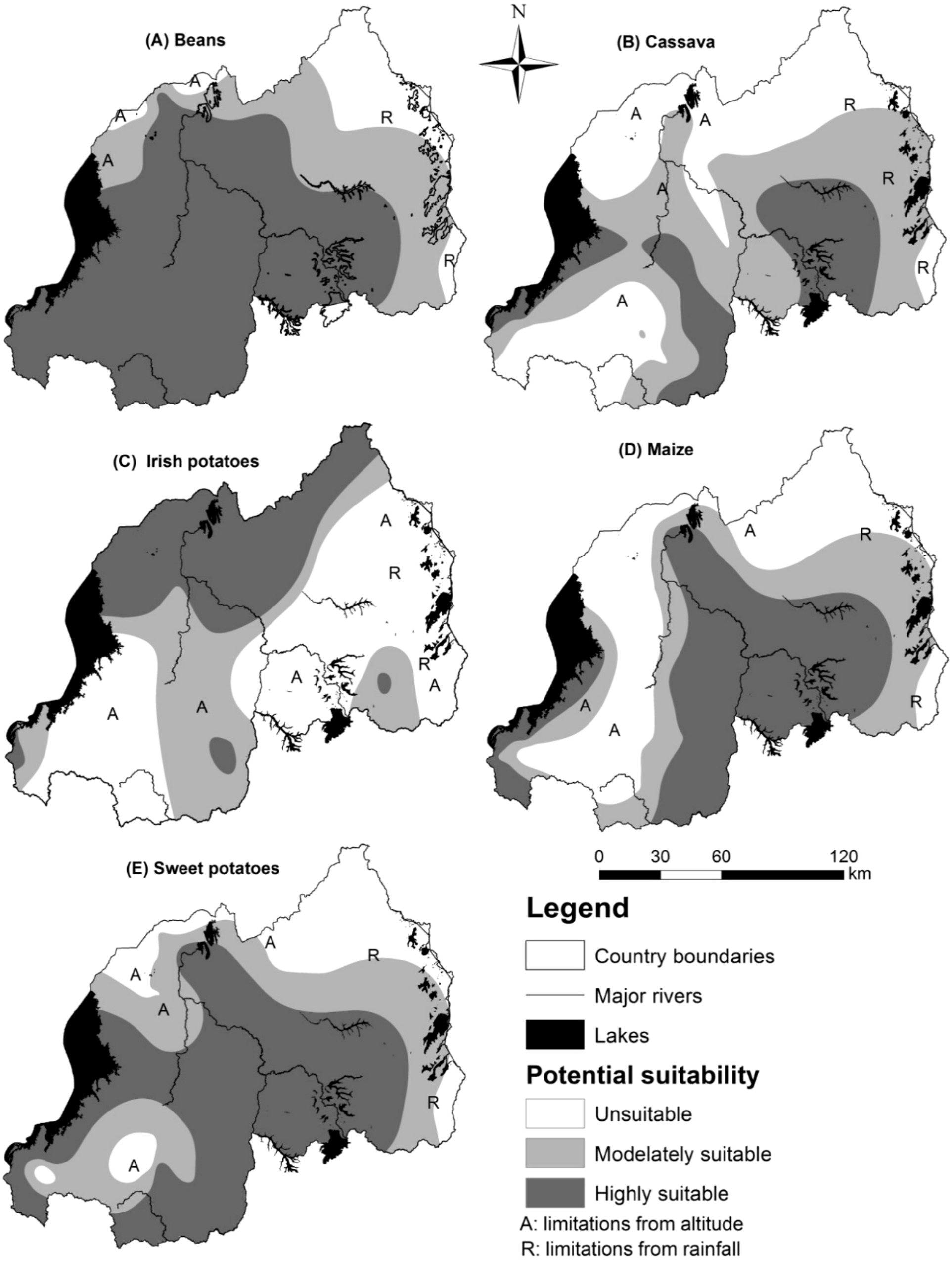

Figure 4. Potential rainfall and topographic suitability for the cultivation of major food crops in Rwanda for the period 2011-2050.

Potential edaphic suitability for cultivation of major food crops

Edaphic parameters are the key soil determinants of crop production (Verdoodt and Van Ranst, 2003). Notwithstanding that, some of these crucial data are not available in many parts of the world especially in developing countries like Rwanda. This could be blamed on the fact that the recording, processing and spatial representation of such data is time-consuming, tedious and expensive. Although edaphic parameters help to determine agricultural productivity, they undergo much more long-term changes that result from complex factors (e.g. population pressure, overgrazing, effects of changes in climate, natural factors, etc.). This means in essence that the impact of soils changes on crop suitability may not be easily estimated at annual or decennial timescales. It is in this regard that the soil maps of Rwanda, published in 1993 by MINAGRI, have been used in an attempt to classify spatially the soil suitability for the cultivation of major food crops in Rwanda for the period 2011-2050 (Figure 6). Whereas a lot more information was needed for accuracy and specificity of classification, the evaluation of soil suitability for cultivation of major food crops in Rwanda has been attempted using clay percentage and soil depth, the two most readily available edaphic parameters in Rwanda (Figure 5). The optimum soil clay percentage and soil depth required for suitable growth of the food crops under investigation are were shown in Table 2.

Table 2. Growth soil limits of the crops investigated in this study.

Crops	Clay (%)	Depth (m)
Beans	20-60%	≥0.75
Cassava	≤35%	≥1.0
Maize	20-60%	≥0.75
Irish potatoes	≤35%	≥0.75
Sweet potatoes	≤60%	≥0.75

Source: Verdoodt and Van Ranst, 2003.

Table 2 shows that cassava and Irish potatoes would do well in coarse textured soils (≤35%), whereas beans, maize and sweet potatoes require a higher clay percentage (20-60%). It is also evident that all the crops under investigation grow best in areas with soil depth of more than 0.75 m. That means in essence that the very shallow and shallow regions (less than 0.5 m) are unsuitable for farming in Rwanda. Surveyors advise that the very shallow soils (with less than 0.25 m depth) should not be cultivated but managed to avoid further degradation.

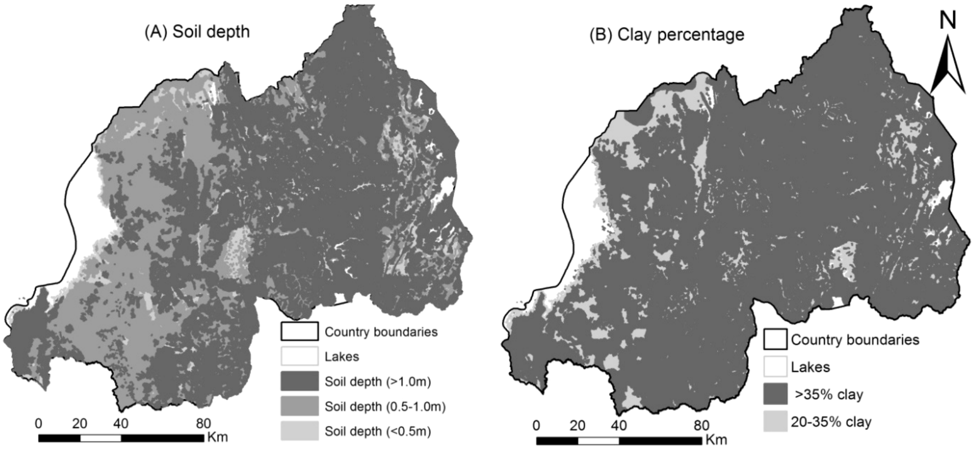

Figure 5. The spatial variations of soil depth and clay percentage in Rwanda.

Figure 5 (A) shows that the shallow soils of between 0 and 0.50 m, are found in very limited and isolated northern, central and eastern regions of the country. The moderately deep soils with 0.50-1.00 m of depth are mostly found in the western region especially over northern highlands and Congo-Nile crest with some isolated pockets in the eastern region. The soils with a depth of more than 1.00 m are found mostly in the south-west, central and eastern regions of the country; i.e. low altitude areas.

The soils with high clay percentage (above 35%) are also located in the central plateau and eastern lowlands, while those with low clay percentage are found in the western region especially the north-western parts of the country (Figure 5 (B)). An attempt to spatially present the soil suitability for cultivation of major food crops in Rwanda has been made using a combination of soil depth and clay percentages requirements as shown in Figure 6.

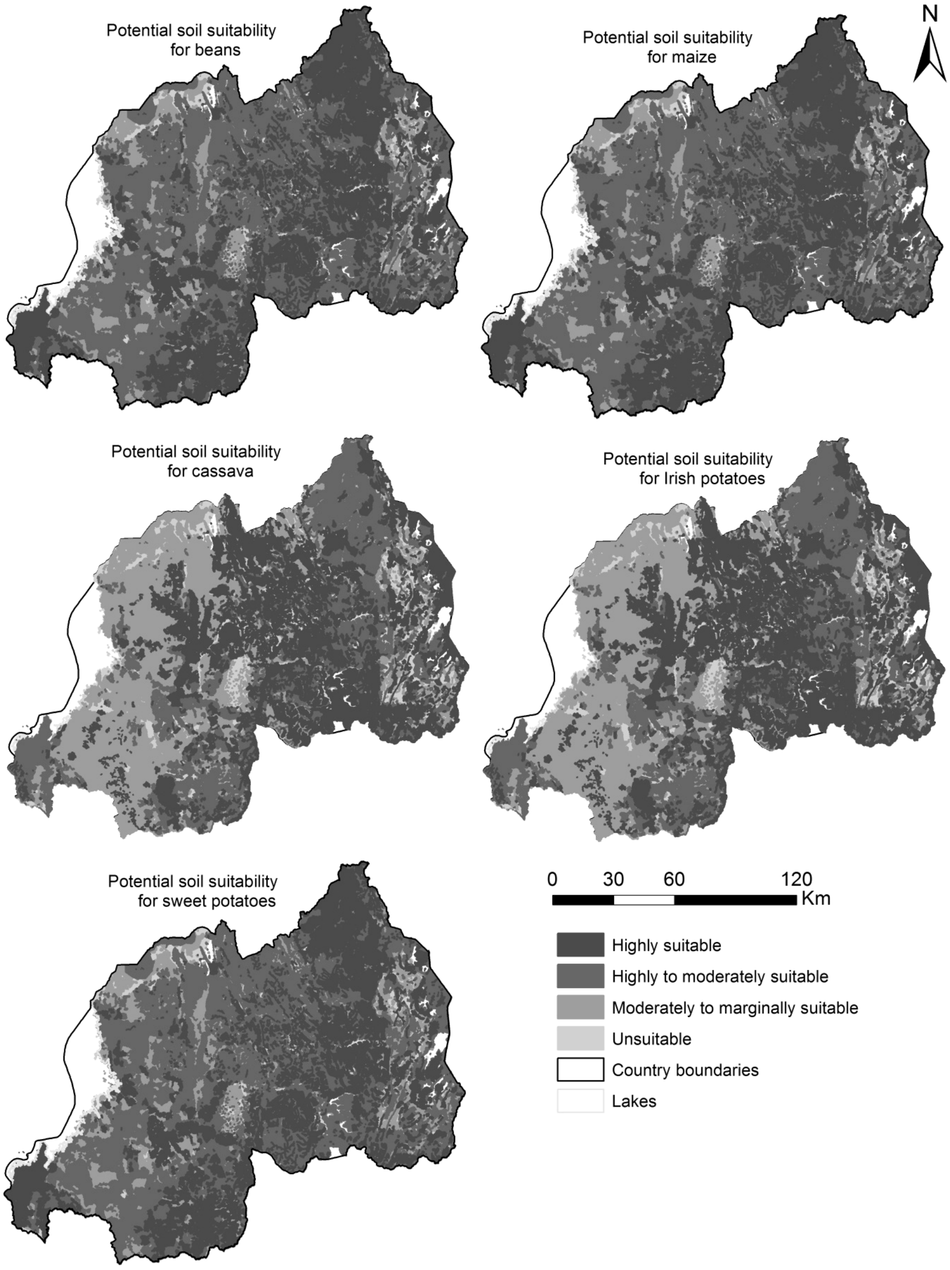

Figure 6. Actual potential soil suitability for cultivation of major food crops in Rwanda.

It is clear from Figure 6 above, that the soils are classified in four categories: highly suitable; highly to moderately suitable; moderately to marginally suitable; and unsuitable, based on the soil limits of specific crop under investigation. The highly suitable areas are those with soils that fall in depth and clay percentage limits, while the unsuitable areas are regions that do not fall in any of these limits (i.e. soil depth and clay percentage). Highly to moderately suitable and moderately to marginally suitable areas have depth and clay percentages that are more or less similar to the above regions, respectively.

The central plateau and the north-eastern lowlands are by far the most suitable areas for growing the food crops under investigation. The north-eastern lowlands have limitations linked with low amounts of rainfall. Therefore, the central plateau is the most suitable region to grow the major food crops in Rwanda considering the climatic and edaphic parameters. Only Irish potatoes do well elsewhere i.e. in the north-western region, which provides suitable climate and topography parameters.

Projected crop yield trends in response to projected climatic conditions

Crops productivity in Rwanda is bound to be impacted by the projected changes in rainfall and temperature along with their adverse effects. The spatial representation of projected yield changes in major food crops over Rwanda (Figures 7 and 8) may serve as a key reference point to estimate the total major food crops production for better planning and taking of adaptation measures in due course.

The projected yield magnitude trends of each of the five major food crops (i.e. beans, maize, cassava, Irish potatoes and sweet potatoes) were seasonally and individually represented (seasons A and B) so as to statistically evaluate the way each crop will be affected by the projected climate change. The statistical yield significance of trends was not represented graphically because the expected seasonal decreasing or increasing patterns in major food crops yields are not significant in most parts of the country.

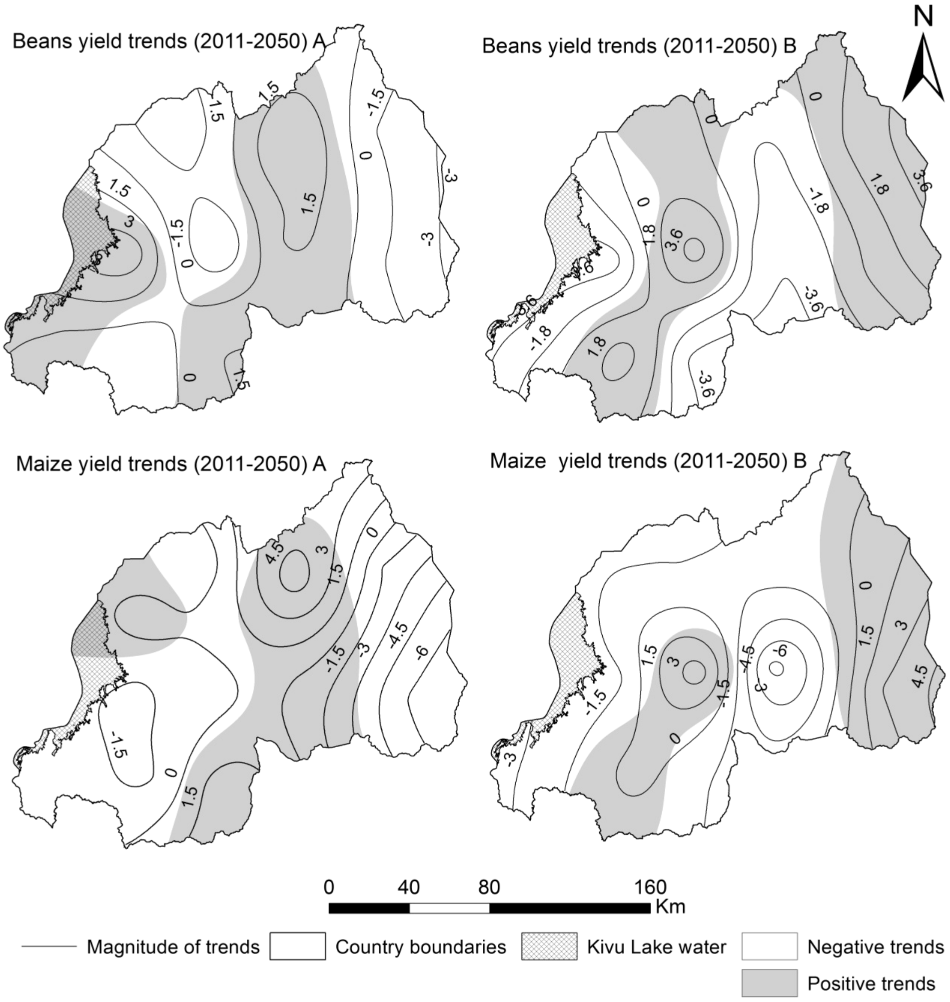

Figure 7. Projected beans and maize yield trends in response to projected rainfall.

The spatial representation of magnitude and direction of crop yield trends at seasonal timescale (Figure 7) forecasts an increase of between 1.5 and 3 kg/ha per year (15 to 30 kg per decade) in beans yields in the south-west and central parts of Rwanda during season A. The rest of the country will show a similar decreasing pattern. Increases in beans yields of between 0.1 and 3.6 kg/ha per year are expected over the Congo-Nile crest and eastern lowlands in season B. The central and western regions will experience an increasing trend of 1.8 to 3.6 kg/ha per year in season B.

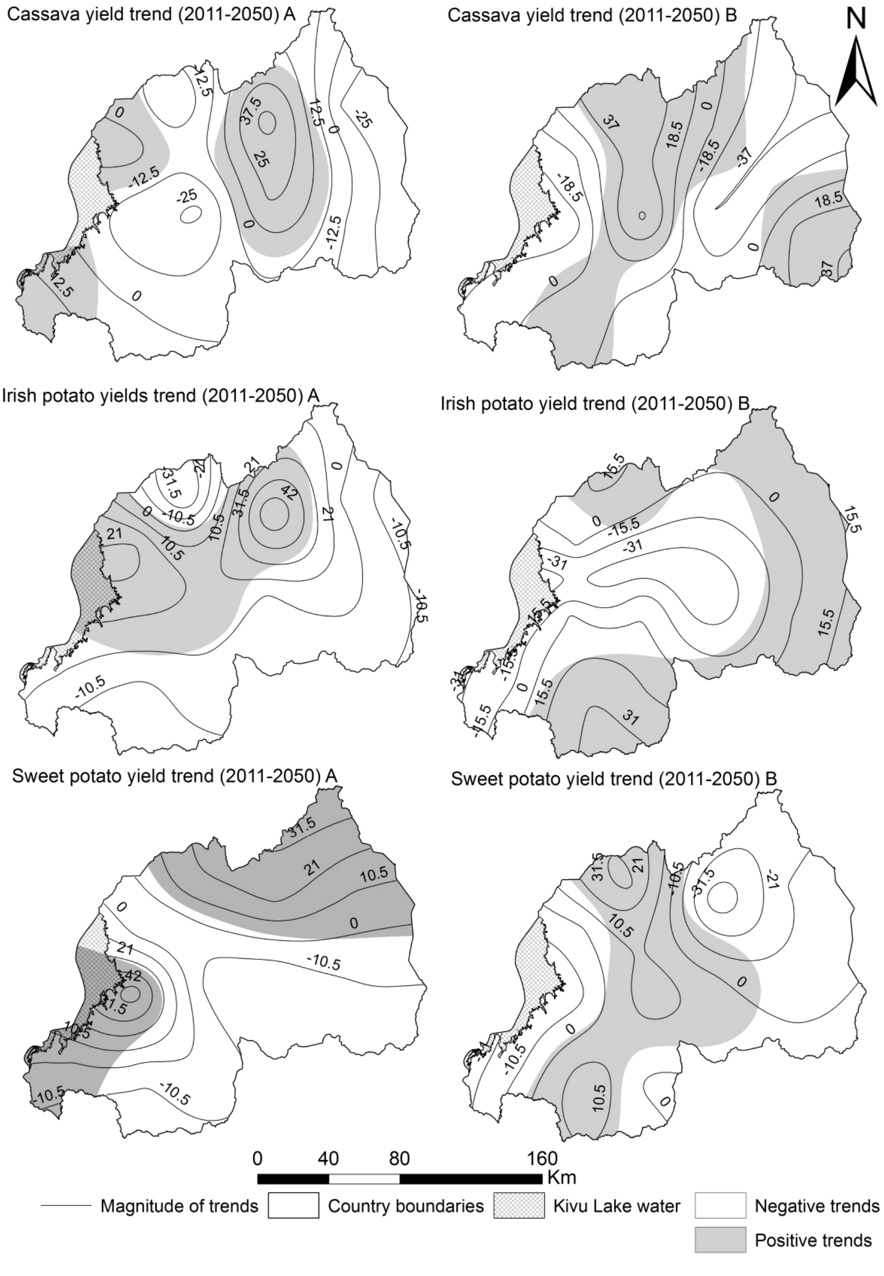

Figure 8. Projected cassava, Irish potatoes and sweet potatoes yield trends in response to projected climatic conditions.

A positive maize yield trend is anticipated over the north-west and the central plateau, at a rate of between 1.5 and 4.5 kg/ha per year (15 to 45 kg/ha per decade) in season A, with the remaining regions (eastern lowlands and western) registering a decline of 1.5-6 kg/ha per season. It is predicted that the south-western Congo-Nile crest and eastern lowlands regions will have an increasing pattern of 1.5-4.5 kg/ha in maize yield in response to projected rainfall and temperatures, whereas a declining pattern of 1.5-6 kg/ha will be seen in the other parts of the country. The same trend is expected to be duplicated for both beans and maize (Figure 7) since they have almost the same agro-climatic requirements (Table 1). It is worth noting that the eastern lowlands are expected to experience reduced bean and maize yield trends during season A, corresponding with projected decline in mean rainfall (Muhire et al., 2014b). A rising yield trend during season B will correspond with the expected decline in mean rainfall.

The south and north-west regions will have an increasing cassava yield pattern of between 0.1 and 12.5kg/ha in season A; 12.5-37.5 kg/ha in the central region; with the rest of the country showing a declining trend of 12.5-25 kg/ha in the same season (Figure 8). A rise in cassava yields of between 18.5 and 37 kg/ha is expected in the central and the south-eastern lowlands regions during season B, with the western, north-eastern and southern regions registering a decline of between 18.5 and 37 kg/ha.

The spatial representation of trend magnitude in Irish potato yields (Figure 9.8) at seasonal timescale reveals that yields will only increase in the north-western region by between 10.5 and 42 kg/ha per year during season A. A small pocket of the north-west area, previously known to be the most productive zone, expects a decline in Irish potato yields as a result of increased mean rainfall and number of rainy days. Flooding episodes, landslides and waterlogging, which destroy the crops, are likely to occur. The Irish potato yields are projected to increase by between 15.5 and 31 kg/ha in the north-western, southern and eastern lowlands regions of the country during season B. Surprisingly, the eastern and southern regions are normally not suited for Irish potato cultivation due to rainfall and altitude limitations. However, a rise in yields might result from the projected increase in mean rainfall and number of rainy days in February-May.

Sweet potato yields are expected to rise by between 10.5 and 31.5 kg/ha per year (105 to 315 kg/ha per decade) over the northern region during season A. The south-west region will have an increasing pattern of between 10.5 and 42 kg/ha per year (105 and 315 kg/ha per decade). There will be a decline of between 0.1 and 10.5 kg/ha per year (1 and 105 kg/ha per decade) in the remaining parts of the country (the west-north, central and south). The positive trend pattern in sweet potato yields of between 0.1 and 10.5 kg/ha per year (1 and 105 kg/ha per decade) is expected to be duplicated over the central region from north to south, with the rest of the country (the western and eastern regions) expecting a decline in yields.

Conclusion

Some climatic (precipitation and temperature data) and edaphic parameters have been used to project crop cultivation in Rwanda. Hence, the central plateau of Rwanda with an annual mean rainfall of between 1000 m and 1300 m, temperatures of between 18 °C and 20 °C and altitude oscillating between 1500 m and 2000 m, is expected to be the most suitable region for growing major food crops. The only exception being Irish potatoes, which are much more climatically and topographically suited for the north-western region. This region is expected to experience an increase in yields for most of the major food crops under investigation, with the south-west region experiencing beans, cassava and sweet potatoes yield increases in season A. The central plateau region will be at high risk after 2050 if the decreasing trend of between 1 mm and 25 mm per decade in mean rainfall and 0.092 to 0.184 days per year in number of rainy days for the period 1993-2050 were to continue (Muhire et al., 2014b).

The eastern lowlands are anticipated to have a decreasing trend in most crop yields in season A in line with the expected decline in mean rainfall and number of rainy days; while the increase in beans, maize and Irish potato yields in season B will be in response to the expected increase in mean rainfall and number of rainy days. Although the north-western region is expected to have an increase in mean rainfall and number of rainy days, it will experience a decline in major food crops yields perhaps due to waterlogging, flooding and landslide, which all destroy crops. It is, then, only fair that the daily rainfall intensity, dry and wet consecutive spells, land and crop management systems are put in place and more detailed edaphic data analysis made for more accurate crop yield predictions to be realised. It is equally important to note that the major food crops may heighten incidences of harmful vectors and pests resulting from changing climate (FAO, 2008). Unfortunately it is difficult to predict the vectors and pests which might result from changing climate in Rwanda to predict their impacts on crop yields.

It is worth noting that the ongoing reforms in Rwanda including land use consolidation policy, which encourages farmers in adjacent lands to grow the same crop; marshland irrigation; one cow per family program, called "*GIRINKA program*" which sets out to integrate livestock keeping in agriculture by increasing the use of manure to enrich the soil; erosion control programs through construction of progressive and radical terraces, among others (MINAGRI, 2008) might play a determinant role in increasing crops productivity in Rwanda, while at the same time having negative impacts on the predictions of crops yields responses to ongoing changes in climate. Therefore, there is a need to intensify the adaptation and mitigation measures to deal with impacts of ongoing changing and varying climate on food crops production for the welfare of Rwanda's population in the coming years.

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