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Estimation of effective fallow availability for the prediction of yam productivity at the regional scale using model-based multiple scenario analysis

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ABSTRACT

Soil fertility restoration and crop performance in many developing countries with low input agriculture strongly relies on fallow duration and management. More precise information about the availability of fallow land may provide a way to improve the simulation of yam (*Dioscorea* spp.) yields at the regional scale which has hardly been considered in prevailing approaches to model regional crop production. The probable reason behind this is scarce availability of data on fallow duration and variation across the farms in a region. Therefore, this study attempts to estimate effective fallow availability for yam production at the regional scale and to simulate the effect of fallow on regional yam yield. Yam growth and yield were simulated with the EPIC model which was incorporated into a Spatial Decision Support System (SDSS) covering a typical catchment with variable land use intensity within the sub-humid savannah zone of West Africa. Yam-fallow rotations were simulated within 1120 quasi-homogenous spatial units (LUSAC = Land Use-Soil Association-Climate units) and aggregated to the 121 sub-basins and ten districts within the catchment under three different scenarios of fallow availability: (S1) Total savannah area was available as fallow land, (S2) 50% of the bush savannah was available as fallow land and (S3) 25% of the bush savannah was available as fallow land. The aggregation procedure adopted in this study was based on changes in the frequency of fallow-cropland classes within the sub-basins to render the SDSS sensitive to changes in fallow availability. Comparison of the average simulated tuber yield with the observed mean yield over the entire catchment showed that the simulations slightly overestimated the yields by 0.4% for scenario S1, whereas, underestimated by 14.2% and 36.8% in scenario S2 and S3 respectively. When compared with the effective fallow availability to maize, it was concluded that, (1) due to farmers preferences to plant yam mainly on virgin savanna land and as the first crop in the rotation after fallow, the effectively available fallow area for yam is higher than for maize and (2) the applied approach is suitable to derive effective fallow availability for yam production at the district scale.

1. Introduction

After cassava (*Manihot esculenta Crantz.*) and sweet potato (*Ipomoea batatas L. Lam.*), yam (*Dioscorea* spp.) is the third most important tropical root crop in West Africa, Central America, the Caribbean, Pacific Islands and Southeast Asia (Onyeka et al., 2006). During the past 30 years, yam production increased threefold with an annual growth rate of 3.8%. A rate of 3% is expected for the next twenty years mostly for the supply of urban markets (Scott et al., 2000). Yam cultivation techniques use very few chemical inputs, the labor is essentially manual and the cultivated varieties are mainly landraces (Scott et al., 2000). In most production systems, yam is grown almost without external inputs following long term fallow (Degras, 1993). This means that yam production depends on the availability of fallow land and expansion of yam production requires that more and more savanna land is cleared for cultivation. Slash and burn techniques remain the common practice for land clearing but are used less extensively due to rapid population growth, high pressure of cattle and changes in land tenure. In the transitional forest-savannah agro-ecological zones of West Africa, fallow periods have decreased from 20 to 30 years in traditional farming to less than 5 years (Ouédraogo, 2004; Aihou, 2003). Therefore, yam yields are reported to decline sharply when grown after short fallow of about 1–3 years duration (Watson

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and Goldsworthy, 1964). Hence, fallow availability and its duration is the main driver for yam production in West Africa (Zannou et al., 2004; Sullivan, 2010). Fallow duration and the ratio between cropping and fallow period strongly influence soil properties, crop yields and cropping sustainability (Szott et al., 1999; Samake et al., 2005; Diekmann et al., 2007). At the farm or regional scale, the relationship between fallow and cropland is reflected by the fallow-cropland-ratio (Ruthenberg, 1980).

Many regional assessments of crop production have been carried out in developed countries or with crops which are usually grown at moderate to high input intensities where the effect of fallow on yield performance is negligible (Thomson et al., 2005, 2006; Liu et al., 2007; Hartkamp et al., 2004; Soler et al., 2007; Challinor and Wheeler, 2008; Gaiser et al., 2008). Only few attempts have been made to incorporate fallow effects into crop modeling at the catchment or regional scale (Van Noordwijk, 2002). However, in order to estimate the effect of fallowing at larger spatial scales, there is a need of new methods to quantify the ratio between the cropland area in a given geographic region and the fallow land area which is available for the farmers to be integrated into their fallow-crop rotation (Gaiser et al., 2010b). Quantification of the cropland area in a given region is relatively easy when agricultural statistics are available. In addition, statistical information about cropland area can also be cross-checked with the results of well established land use classification approaches from remote sensing data. The extent of un-cropped land which is potentially available as fallow land can be derived in the same way from remote sensing information. However, the effective availability and usage of fallow land by the farmer within the fallow-crop rotation is much lower than the potential or apparent fallow area due to several factors like accessibility to the land (which is related to infrastructure facilities), distance of the fallow land from the homesteads and land rights (Brown, 2006). Given the importance of available fallow land for yam production in low-input fallow systems in Benin Republic, methods for estimating the effective fallow availability at the regional scale need to be improved. Therefore, the objective of this paper is to estimate effective fallow availability for yam production at the regional scale by exploring different fallow scenarios and to compare the results with the effective fallow availability for maize as the dominant food crop.

2. Material and methods

The procedure to estimate the effective fallow availability is illustrated in Fig. 1. Spatial information about the location of climate stations, soils, cropland and potential fallow land are combined with assumptions regarding fallow availability into spatial simulation units (LUSAC). The outcome of the scenario simulations at the LUSAC level is aggregated to the district level and then compared to the observed yam yields in order to estimate effective fallow availability for yam production in each district. The components and the procedure are explained in this section.

2.1. Model description

The EPIC model consists of nine integrated sub-models: hydrology, weather, erosion, carbon and nutrient cycling (N, P, and K), plant growth, soil temperature, tillage, economics, and plant environment control (Williams, 1995). In its current form, EPIC is well suited for assessing the effects of soil erosion on crop productivity, predicting the effects of management decisions on soil, water, nutrient, and pesticide movements, and tracing the allocation and turnover of C and N in soil. The model operates on a daily time step and is capable of long-term simulations of up to 4000 years with soil profiles having up to 10 layers.

Table 1
Comparison of observed and simulated mean tuber yield of yam, mean residual error (ME), and mean absolute error (MR) after model calibration at the field scale (Srivastava and Gaiser, 2010).

Treatment	Simulated (Mg ha^{-1})	Observed (Mg ha^{-1})	ME	MR (%)
Control	2.44	2.59	0.15	−5.7
Fertilized	3.72	4.12	0.40	−9.7
Optimum fertilization	3.94	4.12	0.18	−4.3

2.2. Crop growth model

A single plant growth model is used in EPIC to simulate biomass accumulation and crop yield of about 130 crops, each with a unique set of growth parameters (e.g., radiation use efficiency, RUE; potential harvest index, HI; optimal and minimum temperatures for growth; maximum leaf area index, LAI; and stomatal resistance). EPIC is capable of simulating growth for both annual and perennial crops. Annual crops grow from planting date to harvest date or until the accumulated heat units during the simulation equal the potential heat units for the crop (Williams, 1995). EPIC estimates crop yields by multiplying aboveground biomass at maturity by a harvest index. For non-stressed conditions, the harvest index is affected only by the heat unit index. The final HI is estimated based on the potential HI, minimum harvest index, and water use ratio. The model estimates potential biomass based on the interception of solar radiation and the RUE that is affected by vapor pressure deficit and by atmospheric carbon dioxide concentration. Water, nutrient, temperature, aeration, and radiation stresses restrict daily accumulation of biomass, root growth, and yield (Williams, 1995). Stress factors are calculated daily and range from 0.0 to 1.0. For plant biomass, the stress used on a given day is the minimum of the water, nutrient, temperature, and aeration stresses. For root growth, it is the minimum of the calculated soil strength, temperature, and aluminum toxicity stresses. In addition, yield reductions of grain crops are calculated through water stress-induced reductions of the HI. With the EPIC crop model, sensitivity of yam yield to fallow duration relies mainly on mineral nutrition and organic matter management.

A prerequisite to use a field scale model at the regional scale lies in the evaluation of the model performance at different areas in the target region. The EPIC model version 3060 was earlier calibrated for yam growth and yield at field scale in the Upper Oueme catchment of Benin Republic (Srivastava and Gaiser, 2010). This calibration referred to fertilized and unfertilized field trials during 2005–2006. In 2005 and 2006, the mean simulated yields agreed well with the observed means resulting in model errors ranging from 5.7 to 9.7% (Table 1). The model has been applied for yam (Srivastava and Gaiser, 2010), cassava, millets, sorghum (Adejuwon, 2004) and maize with reasonable accuracy except for sites with highly acid soils (Gaiser et al., 2010a). In the present study, EPIC version 3060 has been used at the regional scale within the same catchment where calibration has been carried out (see Section 2.3).

2.3. Study area and simulation units

The Upper Oueme catchment covers an area of 14,500 km^2 within the Republic of Bénin. The climate is tropical sub-humid with mean annual temperature of 26.8 °C and mean annual precipitation of 1150 mm (Mulindabigwi et al., 2008). According to the FAO soil classification (FAO, 2006), the predominant soils are Luvisols with variable depth and coarse fragment content. Soils with plinthic layers occur frequently (Giertz and Hiepe, 2008). Soil texture in most of the cases is sandy in the top layers and loamy to clayey in the subsoil. Soil pH is neutral to slightly acid.