THE DETERMINATION OF NATURAL AGRICULTURAL POTENTIAL IN WESTERN AFRICA USING THE FUZZY LOGIC BASED MARGINALITY INDEX

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ABSTRACT

Agricultural productivity is determined and limited in general by a combination of the natural environment and technical measures. If non-capital intensive management is assumed, the natural potential and constraints are of specific importance for the agricultural land use and its productivity. In this context, the Potsdam Institute for Climate Impact Research (PIK) in cooperation with the Max Planck Institute for Meteorology have developed an indicator for natural agricultural potential or rather natural marginal agricultural sites, the so-called marginality index for agricultural land use on a global scale. The aim of its development was to determine the agricultural potential and to calculate the threat of environmental degradation due to agricultural land use. The index analyses several environmental factors limiting agricultural production under low capital input. But global data with a spatial resolution of 0.5°×0.5° can give only a very general idea about spatial distribution and degree of agricultural marginality. Therefore, same influencing factors but with higher spatial resolution and an adapted fuzzy logic based algorithm were used to calculate the agricultural potential within an iterative process with a spatial resolution of 0.05° for Western Africa focusing on the country of Benin. Beyond this spatial aspect, the applicability of remote sensing data within the approach was also studied. The approach comes out with very encouraging results at a regional scale, proving that valuable information can be derived using remote sensing based data with higher spatial resolution.

Keywords: agricultural marginality, food security, environmental degradation, West Africa

INTRODUCTION

In the 90s, a new transdisciplinary approach within the German Global Change research was set up to describe and model global environmental change, the so-called: *Syndromes of Global Change* (1,2,3). This approach comes up with a new methodology and terminology considering 16 typical global patterns of present problematic man-nature interactions, called *syndromes*. One of these syndromes is the so-called *SAHEL-SYNDROME – overuse of marginal land*. The main focus of the Sahel-Syndrome is on a vicious circle like mechanism that forces poor peasants onto agriculturally marginal lands assuming non-capital intensive management. On marginal sites an intensification of agricultural land use would increase the degradation of the environment and thus, damage the natural production basis, decrease yield, and lead to further impoverishment stimulating an extension of the syndrome (4;5). Case studies in poor countries analysing peasant agroecosystems indicate that this core mechanism or kernel of the syndrome describes the position of many people in developing countries, caught in a typical socio-ecological trap (e. g. 6;7).

The process of identifying the proneness of whole regions towards specific syndromes due to natural factors on the one site and social factors on the other site comes out with the so-called *disposition* of a syndrome. Hence, one characteristic within the definition of dispositions is their persistence over long time periods as they are merely modified by the dynamics of the syndromes. The marginality index of agricultural land use has been developed as the indicator for natural marginality analysing several environmental factors, which limit agricultural production under low capital input. On naturally marginal agricultural sites the natural conditions limit further intensification or expansion of agricultural land use, as it would damage the natural product basis. Using distribution and level of the marginality index, the natural agricultural marginality, fragile regions of low productivity can be identified. The indicator can be considered as an early warning indicator identifying endangered regions where even a moderate intensity can easily lead to natural degradation on agriculture sites of a low technological stage (4,5). Furthermore, regions with naturally high agricultural potential, which means sites, where an increase of yields by intensification of agricultural activities is unproblematic, can be identified. For that reason, high potential areas are of specific interest for regions facing problems of growing population, poverty and scarce land resources like many countries of Western Africa. The importance of such sites increases even more, if they are not under agricultural use yet.

But global data and a rather low spatial resolution of 0.5°×0.5° (equivalent about 50×50 km² for Benin) can illustrate only the general distribution and degree of agricultural potential and marginality attaining little information for national and international decision makers to successfully cope with the natural agricultural resources. Thus, we have analysed whether the approach with very promising results on a global scale is feasible on a regional scale, too. The study is part of the interdisciplinary IMPETUS-Project (An integrated approach to the efficient management of scarce water resources in West Africa: Case studies for selected river catchments in different climatic zones). The participants have gathered detailed and broad knowledge about this region over several years (8). In an iterative approach, the marginality index is determined for Western Africa with a spatial focus on Benin with the same influencing factors but with higher spatial resolution and an adapted fuzzy logic based algorithm. Data with high temporal and spatial resolution achieved from remote sensing are interesting and promising tools for this approach increasing the spatial resolution and actuality of the results.

METHODS

Study area

In this study, Western Africa is delimited by the Mediterranean in the north, the Atlantic in the west and south and the eastern national boundaries of Tunisia, Algeria, Niger and Nigeria in the east (20°W - 25°E and 4° - 37.85°N). The region contains various environmental conditions for agricultural land sites, which include fertile coastal areas and the high mountains of the Atlas in the north, the desert Sahara, the Sahel and Sudan Zone, Guinea coast and the tropical rain forest in the south. The generally traditional agricultural land use is characterised by no or non-intensive capital and energy management methods (e.g. shifting cultivation and agroforestry). Consequently, the natural potential of agricultural production represents the most important factor determining yields. Furthermore, societies are formed strongly by agriculture, which still gives work to the majority of people (e. g. 9,10,11,12,13).

Data

For the evaluation of the marginality index, several natural constraints limiting agriculture were quantified and summed in one integrative index: low natural plant production, restrictions due to temperature or light, high aridity, precipitation uncertainty, water limitation, poor soils and the risk of erosion due to the steepness of slopes. Beyond these constraints, the compensation of natural aridity by irrigation owing to near inshore waters has been taken into account as it can be implemented even with low capital input. According to (4), for the incorporation of these factors, the following six indicators have been used for the assessment of the index:

1. Net primary productivity of potential natural vegetation (*NPP*)
2. Aridity coefficient (*AC*)
3. Internal variability of the seasonal precipitation pattern (*PV*)
4. Potential irrigation capacity (*IC*)
5. Soil fertility (*SF*)
6. Slope (*SL*)

In a first step of the iterative approach (Figure 1), comparable indicators in a higher resolution were set up. Therefore, the dilemma was that these data sets or their specific components have not been feasible for processing for Western Africa in a high spatial resolution. But for an accurate evaluation the data sets need to be comparable. For that reason, two data sets namely NPP and AC were made available by PIK, described in more detail in (4). According to the other four data sets PV, IC, SF and SL, data sets with higher resolution could be received. Thus, the resolution of the data sets still varies. In the following, the data sets with a focus on the four which could be already processed in a higher resolution will be described in detail.

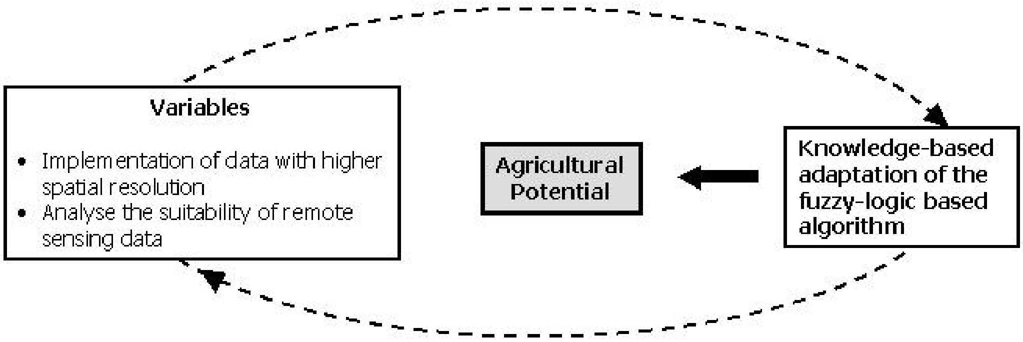

Figure 1: The iterative approach to determine the agricultural potential

The **net primary productivity of potential natural vegetation (*NPP*)** is the fundamental basis within the determination of the marginality index for agricultural land use (Figure 3). As no overall accepted model exists caused by missing census on either the relevance of specific parameters or the participating processes, the arithmetic average of five different models were used, which were also used in the original approach. Matthias Plöchl presented this averaged global model at the IGBP: DIS-GAIM GCTE (International Global Biosphere Programme: Data and Information System, Global Analyses Interpretation and Modelling, Global Change and Terrestrial Ecosystems) NPP-Workshop in Potsdam 20-22. June 1995, see (4) for more details:

1. High Resolution Biosphere Model (HRBM) (14)
2. Terrestrial Ecosystem Model (TEM) (15,16)
3. CARbon Assimilation In the Biosphere (CARAIB) (17)
4. Frankfurt Biosphere Model (FBM) (18,19)
5. Projected Leaf Area Index (PLAI) (20,21)

The **Aridity coefficient (*AC*)** was estimated from the ratio of annual sums of daily actual and potential evapotranspiration (see (4) page 140). Actual evapotranspiration correlates with soil water availability, which can be calculated with a simple bucket model (2). Using the Priestley-Taylor method, potential evapotranspiration has been assessed. Both model and calculation are described in detail in (22).

The **Internal variability of the seasonal precipitation pattern (*PV*)** is based on negative anomalies of monthly precipitation data within the growing season (see (4) p. 141). Therefore, monthly sums of precipitation from 1961 – 1998 from the so-called Hulme data set 'CRU0.5°lat/lon gridded monthly climate data' with a spatial resolution of 0.5°×0.5° processed by the University of East Anglia were used (23). The duration of the growing period can be derived either from climate data (9) or from remote sensing data taking into account the phenology of the vegetation during a year (see e. g. (24,25). For this study, the phenological approach was implemented. Thus, maxima of the monthly Normalized Difference Vegetation Index *NDVI* (from 1981 to 2001) with a spatial resolution of 8 km × 8 km were used. The images have been derived from the Advanced Very High Resolution Radiometer (AVHRR) sensor on board of the NOAA satellite ('NOAA/NASA Pathfinder AVHRR Land Program') (26).

The **Potential irrigation capacity (*IC*)** was calculated from the inshore water density and slope using the hierarchically structured inshore water network from ARC/WORLD^{TM} by ESRI (27) and the slope data set from 'HYDRO1K' produced by a cooperation of EROS Data Centre and USGS (28). The latter is founded on the global 30 arc-second hydrological corrected digital elevation model named GTOPO30. The spatial resolution of the data from ARC/WORLD^{TM} is about 25 km $\times$ 25 km and the one of HYDRO1K is 1 km $\times$ 1 km. To evaluate the potential irrigation capacity, the slope and inshore water density were normalised to the interval [0,1] adapted to the descriptions in (4), pp. 141f. For Benin, first investigations with the X-SAR digital elevation model (DEM) from SRTM (Shuttle Radar Topography Mission) come out with very encouraging results, which will be continued.

Soil fertility (*SF*) is an elementary basis for agricultural land use and satisfying yields. Leemans and van den Born (29) have developed a database with soil properties based on the soil classification of the global soil map (30). From this classification scheme, the fertility factor S_f was chosen.

To consider the suitability of a terrain, the topographic constraint **Slope (*SL*)** is used incorporating the risk of erosion. Therefore, the same data from USGS described above have been used.

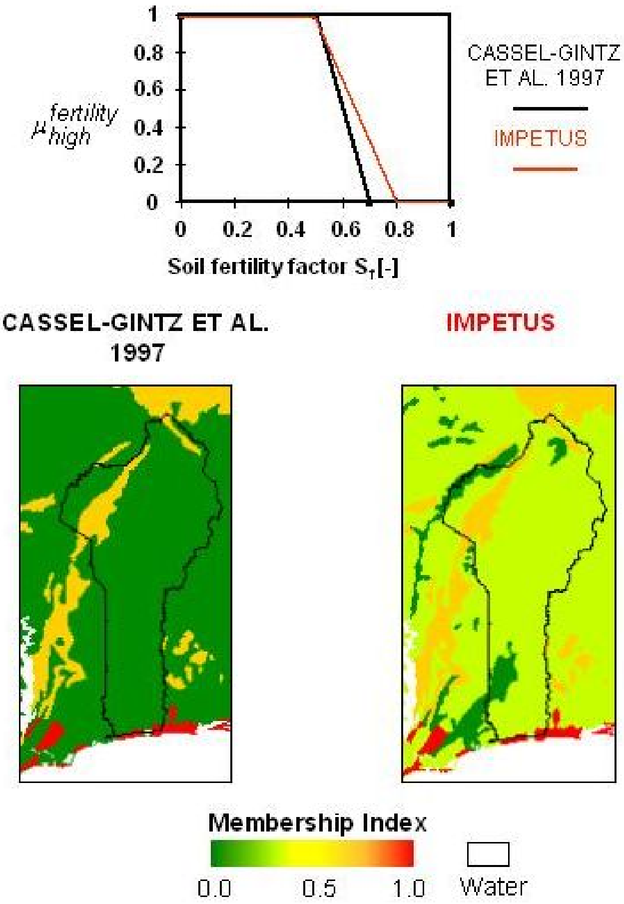

Fig. 2: Fuzzyficated soil marginality according to the algorithm by Cassel-Gintz et al. (4) (left) and to the knowledge-based adaptation by IMPETUS (right) exemplified for Benin.

Fuzzy based algorithm

Following the definition of the input variables, these six input data sets were fuzzyficated according to regional knowledge, empirical observations or measurements in a second step. In this case, fuzzyfication means that for each site (pixel) of the input data set a degree of membership of linguistic categories (low, high etc.) is set up in relation to its contribution to the marginality of agricultural land use $\mu_{ling.cat.}^{variable}$ $(0 \leq \mu \leq 1)$ (4,31). Each membership ranges from 0 to 1. Hence, a degree of 0 indicates no limitation of agricultural land use and thus naturally high potential sites (e. g. tropical areas with fertile soils), whereas 1 indicates sites, where a reasonable agriculture because of this natural constraint is not possible (e. g. desert). Between these two values, a linear term of the membership function is assumed. The broad knowledge gathered within the interdisciplinary IMPETUS-Project over several years, particularly in Benin and Morocco has been used to define the membership function and if necessary to adapt the fuzzy-logic based algorithm. Figure 2 illustrates such an adaptation of the algorithm exemplary for the variable 'soil fertility' due to regional expert knowledge within the project.

In a third step, these fuzzyficated variables were combined using a logical decision tree (see in more detail (4) p. 137f. Within the decision tree all arguments for or against agricultural marginality are summed using fuzzy logic operators (see Figure 3). These were already briefly described above. Generally, the most used ones are fuzzy AND (minimum) and fuzzy OR (maximum) operators (31). Beyond these non-compensatory operators, two compensatory fuzzy operators are set up within the evaluation of the marginality index: 'Compensatory AND' (or 'Lukasiewicz AND') and 'Asymmetric-compensatory OR' (see (4) p. 148). With the compensatory AND for instance, the following conditions can be incorporated: without existing irrigation capacities, natural aridity cannot be reduced, whereas middle irrigation availabilities can decrease high aridity to some extent and can compensate medium aridity totally. With the wide range of fuzzy logic operators all necessary relationships between two variables within the decision tree can be implemented.

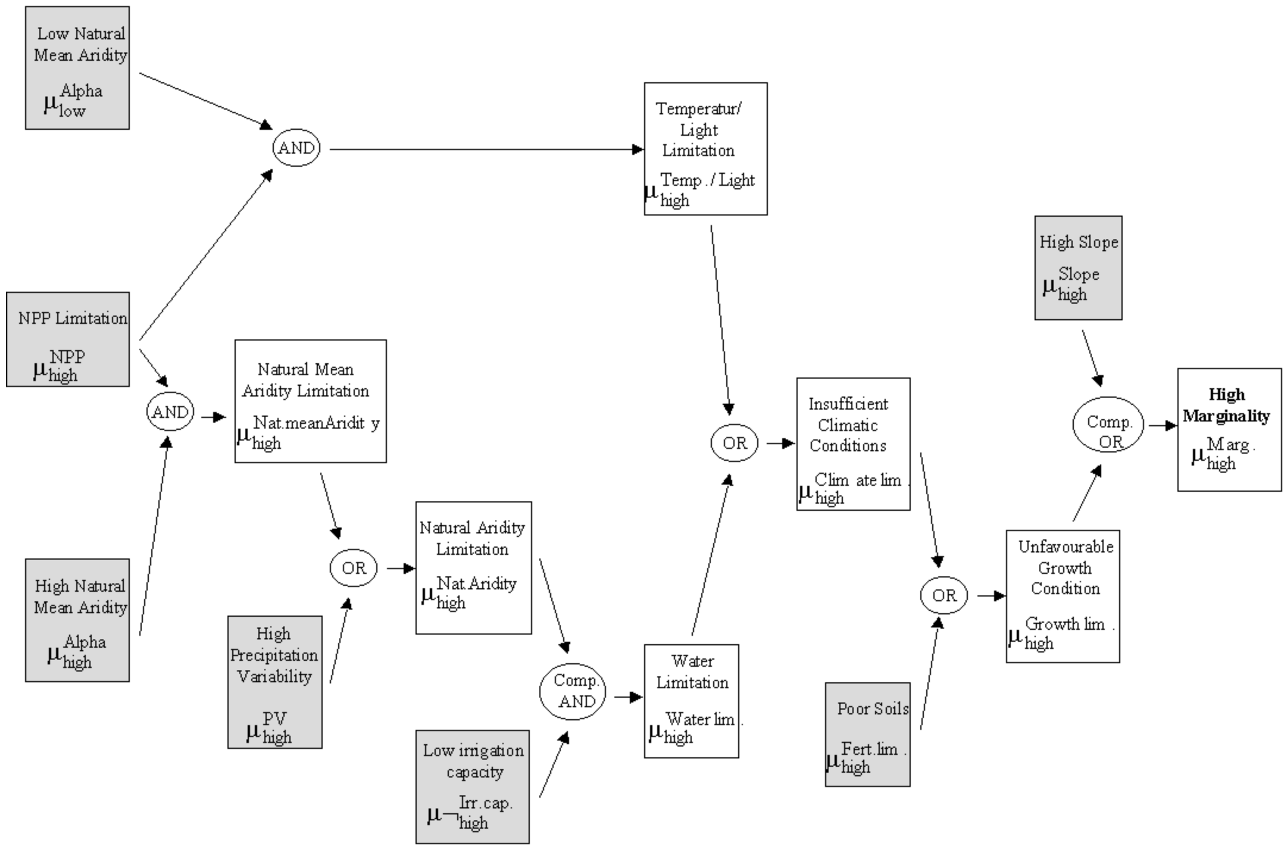

Figure 3: Decision tree evaluation of the natural marginality of agricultural production with different fuzzy logic operators (circles); the six base input variables are shown in grey colour boxes (modified after (4) p. 138)

RESULTS

The agricultural potential and risk of environmental degradation due to intensification of agricultural activities are calculated with the marginality index of agricultural land use for Western Africa with a spatial resolution of 0.05°×0.05°. Whenever possible input variables with higher resolution have been used than those at the original determination by (4). Therefore, data with higher temporal and spatial resolution derived from remote sensing like *NDVI* images or digital elevation models are interesting and promising tools. Due to very good regional expert knowledge within the IMPETUS Project, the fuzzy-logic based algorithm has been adapted successfully representing natural potential and constraints of agricultural land use for the region in more detail.

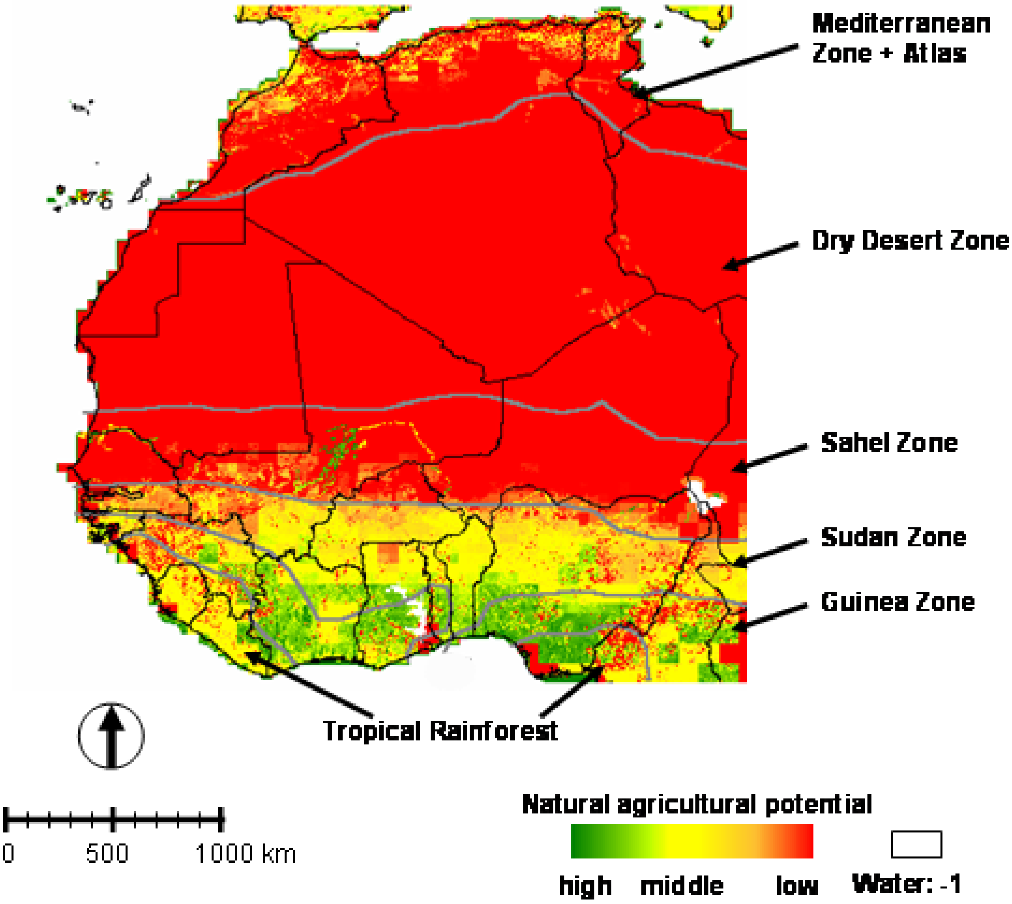

Figure 4: The natural agricultural potential for Western Africa using the marginality of agricultural land use overlaid with agro-climatic zones derived from the precipitation data set; resolution: 0.05°×0.05°.

As Figure 4 shows, good or medium marginal agricultural areas are mainly situated within fertile plateaus, oases and along the coastlines or rivers in North Africa. Indeed, the majority of agricultural yields are made there, although spatially limited, mainly due to irrigation. In Morocco, for instance, irrigation systems deliver 45% of the whole agricultural production (32,33). Steep slopes in the Atlas Mountains and arid conditions in southern parts are severe constraints for agricultural production within most parts of North Africa. Due to the high aridity and unfavourable soils, the Sahara desert and Sahel zones are characterised by maximum natural marginality. Merely near rivers like Niger or Senegal, the aridity can be compensated and medium or even low marginality values can be achieved. There, greater fields with sorghum, maize and cash crops like cotton or vegetables like e.g. nearby Niamey are cultivated due to irrigation and flood agriculture (9,34). Beginning with the Sudan Zone, the naturally based agricultural potential increases further up to the South due to sufficient climatic conditions with increasing average annual precipitation and declining rainfall variability and thus, increasing *NPP* values and partly fertile soils. In mountainous areas like the highlands of Guinea, steep slopes constrain agricultural production as well as poor soils in some areas of the humid tropics. Hence, the map represents the natural conditions and limitations of agricultural land use according to literature and local knowledge pretty well (9,10,11,12,13,32).

CONCLUSIONS

Low or medium agricultural potential sites dominate within Western Africa and only few sites allow reasonable and intensive agricultural production with high yields. But the majority of these productive fields are used for cash crops in Western Africa and thus they do not improve food security of the rural population (32,10,34). Furthermore, increasing population forces the pressure on natural resources leading to an expansion and intensification of agricultural land use and increasing conflicts and migration. This has already resulted in e.g. desertification and land degradation in several areas of Western Africa (9,33,10,35,6,7). In Benin, for instance, dramatic change within the man-nature system can already be noticed, resulting in increasing conflicts between resident peasants and mobile livestock owners (36). Hence, the need to overcome these threats for men and environment will be one essential challenge in the future.

The fuzzy-logic based marginality index of agricultural land use is a suitable measure also for the calculation of the agricultural potential on a regional scale. In comparison with the result by (4), the regionalization shows a more detailed representation of the natural conditions and constraints of the agricultural production. However, one has to keep in mind that the different spatial resolution of the input variables comes out with problems while combining the data pixel by pixel and artificially implementing improvements of the spatial information. These problems are especially obvious along coastlines.

Due to the serious consequences expected especially for Africa, the detailed current information has to be gathered and early warning systems and indicators have to be established to identify vulnerable sites (37,38). Data with higher temporal and spatial resolution derived from remote sensing are therefore interesting and promising tools. Moreover, several of the input variables are rather stable, so with remote sensing data sets a reflection of actual trends of processes like desertification or climatic change as well as the calculation of future scenarios could be simplified. Beyond that, the implementation of socio-economic parameters like increasing population pressure is a challenge for our further studies modelling the agricultural potential of Benin.

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