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Eduardo Maruyama, Máximo Torero, Phoebe Scollard, Maribel Elías, Francis Mulangu, and Abdoulaye Seck

Frontier analysis and agricultural typologies

PARI

Bonn, March 2018

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Acronyms and abbreviations

AEZ	agroecological zone
AGRODEP	African Growth & Development Policy Modeling Consortium
BMZ	German Federal Ministry for Economic Cooperation and Development
DEA	data envelopment analysis
FAO	Food and Agriculture Organization of the United Nations
GIS	geographical innovation system
ICT	information and communication technology
IFPRI	International Food Policy Research Institute
OECD	Organization for Economic Co-operation and Development
PARI	Program of Accompanying Research for Agricultural Innovation
PCA	principal component analysis
R&D	research and development
SEWOH	One World, No Hunger Initiative
SFA	stochastic frontier analysis
ZEF	Center for Development Research

Executive Summary

PARI's main goal is to contribute to sustainable agricultural growth and food security in Africa and India by supporting the scaling of proven innovations in the agri-food sector in collaboration with all relevant actors. PARI accompanies specified innovations with ex-ante impact research and identifies further innovation opportunities, including those expressed by end users of research in collaboration with the multi-stakeholder innovation platforms. Within PARI's work, AGRODEP and IFPRI have the task of assisting in the development of a methodology and concept for strategic analysis and visioning by providing economic modelling tools to help understand where the best opportunities for innovation investments in value chains are. For this purpose, IFPRI has constructed agricultural typologies of micro-regions for 8 of the 12 African countries in PARI to identify micro-regional level opportunities, bottlenecks and investment gaps based on the concept of the production possibilities frontier applied to farm activities, drawing on highly detailed household-level survey and geospatial data on agroecological conditions, accessibility and poverty.

The stochastic frontier approach allows the econometric exploration of the notion that, given the fixed local agroecological and economic conditions in a micro-region and the occurrence of random shocks that affect agricultural production (weather, prices, etc.), the investment, production decisions and technological innovations a farmer makes translate into higher or lower production and income. In such a context, inefficiency is defined as the loss incurred in by operating away from the frontier given the current prices and fixed factors faced by the household. By estimating where the frontier lies, and how far each producer is from it, the stochastic frontier approach helps to identify local potential and efficiency levels to construct the typology.

With this estimation approach estimates are obtained that allow for the prediction and extrapolation of agricultural income potential and efficiency measures at the regional level, which can then be grouped and classified into types to construct the typology. The typology then allows the identification of types of regions with extremely different needs, bottlenecks and opportunities, which in turn will result in a different set of investment recommendations for development in each type of region, including decisions regarding investments in agricultural innovation.

Keywords: Production Efficiency Measures, Agricultural Policy, Rural Development, Economic Geography.

JEL codes: D24, O13, Q18, R11, R12.

1 Background

Africa is increasingly emphasizing the role of innovation in development. Innovation for sustainable and high agricultural growth forms an important part of the Science, Technology and Innovation Strategy for Africa 2024 (STI Strategy 2024). The German Government has acknowledged this innovation potential and wants to support the improvement of food and nutrition security and sustainable agricultural value chains through Agricultural Innovation Centers in 12 African countries and in India. ZEF's Program of Accompanying Research for Agricultural Innovation (PARI) offers independent scientific advice to support these Innovation Centers.

PARI's main goal is to contribute to sustainable agricultural growth and food security in Africa and India by supporting the scaling of proven innovations in the agri-food sector in collaboration with all relevant actors. PARI accompanies specified innovations with ex-ante impact research and identifies further innovation opportunities, including those expressed by end users of research in collaboration with the multi-stakeholder innovation platforms. PARI also fosters synergies with and links to existing innovation systems in the respective countries.

Within PARI's work, AGRODEP and IFPRI have the task of assisting in the development of a methodology and concept for strategic analysis and visioning by providing economic modelling tools to help understand where the best opportunities for innovation investments in value chains are. For this purpose, we have constructed agricultural typologies of micro-regions for 8 of the 12 African countries in the PARI project to identify micro-regional level opportunities, bottlenecks and investment gaps based on the concept of the production possibilities frontier applied to farm activities, drawing on highly detailed household-level survey and geospatial data on agroecological conditions, accessibility and poverty. The rest of this report is organized as follows. Section 2 presents a brief literature review. Section 0 explains the conceptual framework behind the typology approach and how this work falls within the larger scope of the modeling work in PARI. Section 0 describes the methodology developed to construct the typologies. Section 0 presents the main results of this study and Section 0 concludes.

2 Literature review

Agricultural development depends on innovation, widely recognized as a major source of improved productivity, competitiveness, and economic growth, while also playing an important role in creating jobs, generating income, alleviating poverty, and driving social development (OECD, 2009). Agricultural innovation is a process that goes beyond conventional lineal models of knowledge and technological transfer (from researcher to extension agent to farmer, or vice versa), and is instead the result of a complex system of interactions between these and many other actors, practices, rules, that take place in a complex environment (Spielman et al., 2009; World Bank, 2012). This environment, characterized by its multidimensional nature (biophysical, technological, sociocultural, economic, institutional, and political), sets the space in which the interactions between different levels (international, national, regional, and local), and the restrictions and interests of different stakeholders (producers, government, researchers, etc.) interact over time to generate agricultural innovation (Schut et al., 2014; Giller et al., 2008; Funtowicz and Ravetz, 1993).

Poverty maps have been one of the most widely used tools to guide and target rural development policies by providing a method to measure the spatial location of the poor using household survey and census data (Lanjouw, 1998; Hentschel et al., 2000; Elbers et al., 2001; Deichmann, 1999).[1] Global maps of agroecological zones (AEZs) (FAO, 1978; Fischer et al., 2002), land cover and land use (Anderson et al., 1976, Loveland et al., 2000) have also helped prioritize agricultural investments by identifying the spatial heterogeneity in the conditions for, and the performance of, agricultural activities in any region of the world. However, understanding the biophysical and economic dimensions of the environment in which agriculture and agricultural innovation take place requires an approach that combines economic, statistical, and spatial analysis tools.

There have been some efforts to guide investments in agriculture and agricultural innovation through spatial and statistical classifications of regions or farms. Cluster analysis approaches have been used to identify types of farms and farming systems associated with better adoption rates of new technologies (Bidogeza et al., 2009; Hardiman et al., 1990). Bryan et al. (2011) develop a method for calculating a spatial measure of expected profits from agricultural land to guide landscape planning for natural resource management to increase the cost-effectiveness of environmental investments through spatial targeting. Byerlee (2000) makes the case for using mapping tools that combine agroecological and socioeconomic variables to improve targeting of research investments for poverty alleviation, while Bigman and Loevinsohn (2003), studying specific cases in Sub-Saharan Africa, point out that the

[1] See also Bigman and Fofack (2000) for a comprehensive review of GIS applications for targeting poverty alleviation programs.

effectiveness of these geographical targeting efforts can be significantly increased when regional disparities are large. Bellon et al. (2005) use small area estimation methods and spatial analysis to combine, through cluster analysis, poverty maps and georeferenced biophysical data relevant to maize-based agriculture in Mexico to improve stratifying and crop breeding efforts to meet the demands of poor farmers.

3 Conceptual framework[2]

Several of the studies mentioned in the previous section have linked agricultural potential and need-based criteria to target development oriented investments by combining agroecological and poverty data. However, to fully address the link between agricultural driven growth and poverty reduction, it is key to include in these assessments the economic components of the environment in which smallholders operate, such as market prices and the degrees of access to those markets. For investments in agricultural innovation to be sustainable, farm-level increases in productivity need to be translated into higher incomes and better livelihoods for rural households. Our proposed approach attempts to bridge that gap by mapping estimates of agricultural potential and efficiency under the framework of production theory applied to agriculture by combining agroecological, poverty, market, and farm-level information (see Figure 1).[3]

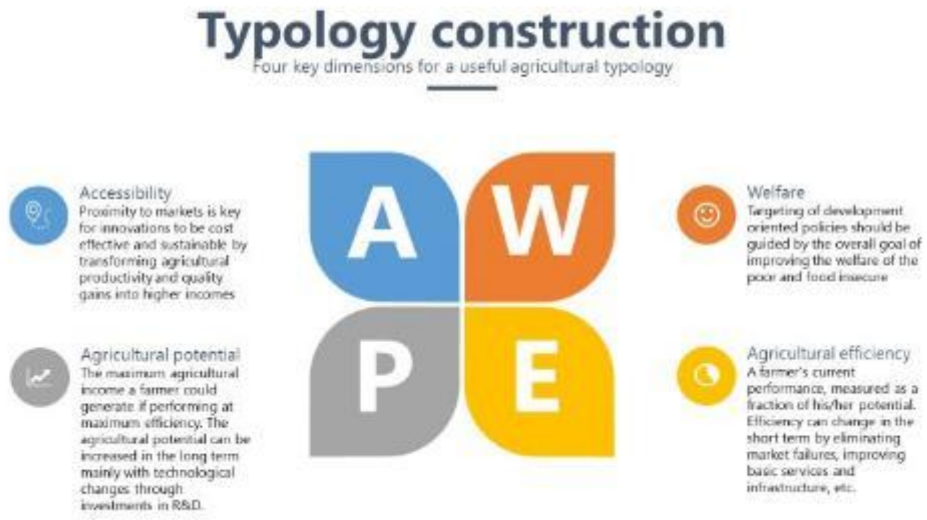

Figure 1: Four key dimensions to characterize the regional heterogeneity of the agricultural environment

The idea behind the concept of agricultural innovation is to allow agricultural education, research, and extension to contribute substantially to enhance agricultural production and reduce rural poverty. Hence, when deciding where to invest and introduce innovations in agriculture, priority should be given to areas where rural poverty is high and increases in

[2] This section explains the rationale for the typology work as a standalone element of the PARI modeling work, but it should be noted it is also a piece of a larger set of modeling tools that feed into each other: a general equilibrium economic model, crop models, and a visualization tool (eAtlas).

[3] The institutional framework is also central to the characterization of the environment in which agricultural innovation takes place, but we do not explicitly include it in this analysis as in most cases it is set at the national level and this study focuses on identifying factors that explain heterogeneity at the sub-national level.

agricultural production would be more beneficial. However, high poverty areas can be very heterogeneous both in terms of what their current agricultural potential is, and how much of this farmers are able to attain by operating efficiently. For example, poor areas with high agricultural potential and low efficiency would benefit the most from innovations that help farmers reduce the specific short-term inefficiencies they face, while poor areas with low potential would require frontier shifting technological change attainable only through long-term investments in R&D. This idea is depicted in Figure 2.

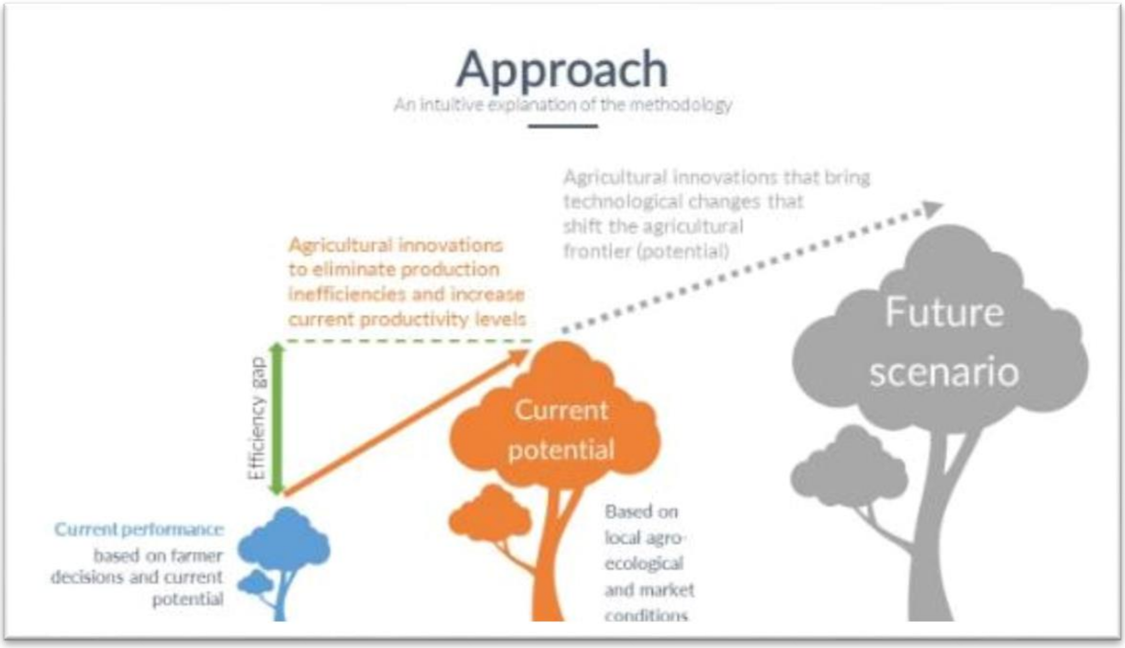

Figure 2. Role of efficiency vs. potential oriented agricultural innovations

Since the objective of the typology is to systematize the way in which analytical information is presented, it is necessary to specify the criteria used to group the estimates for agricultural potential, agricultural efficiency, and poverty into *classes* or *types*. While there are several ways of choosing such criteria depending on specific user needs, the common idea behind this typology approach is based on the following building blocks:

1. *Priority,* which describes a region's degree of *urgency* for investments in development, measured in terms of the wellbeing of the local population and the ultimate target beneficiaries of agricultural innovation efforts. For the eight countries in this report we will use poverty rates as the preferred measure of regional welfare, because of their availability and consistent measurement (although other measures such as malnutrition (stunting) rates, which would approximate regional food security status, could also be used.
2. *Agricultural (income) potential,* which establishes the maximum agricultural income smallholders in a region can attain if performing at maximum capacity (their own, as

well as of the markets, productive infrastructure, and basic services surrounding them). Agricultural income potential is determined by both the biophysical factors that condition agricultural production and the economic factors that influence crop prices. Under perfect conditions, it is the interaction of these two sets of elements that establishes the maximum income a farmer can earn from agricultural activities. To increase their agricultural income potential, farmers require long-term investments in R&D that completely shift the productive paradigm through technological change.

3. *Agricultural (income) efficiency*, which describes how much of the potential described above is attained by farmers in a region under current conditions. To increase their efficiency, farmers need to reduce transaction costs in agricultural production and marketing through improved infrastructure (such as roads) and services (such as market information), overcome market failures (access to credit, insurance, land markets, etc.), and receive better access to basic services (such as education and extension services).

With these building blocks, we will classify regions per the following types:

Table 1: Typology classification

	Poverty	Potential	Efficiency
Critical with moderate agricultural opportunities	High	Moderate	Any
Medium priority with moderate agricultural opportunities	Medium	Moderate	Any
Low priority	Moderate	Moderate	Any
High priority	High	Medium / High	Medium / Moderate
Medium priority with high agricultural opportunities	Medium	Medium / High	Medium / Moderate
Low priority with high agricultural opportunities	Moderate	Medium / High	Medium / Moderate
High performance	Moderate	Medium / High	High

As a policy tool, the typology can provide some general guidance on what are the best types of interventions for each region (Table 2). For example, development efforts in critical areas (red) should focus on long-term investments to increase agricultural productivity through technological changes and large-scale infrastructure projects, combined with short-term safety net programs that provide immediate assistance and incentivize investments in human capital (through programs like conditional cash transfers) to increase off-farm opportunities in rural areas. In poor areas with higher agricultural potential (darker shades of green), innovation investments should focus on reducing the inefficiencies that are preventing farmers in those regions from performing closer to the frontier. While not necessarily a priority from the poverty reduction perspective, farmers in high performing areas (light green) should be the focus of analysis as potential drivers for farmer-led innovation, and be the recipients of institutional innovations (through vertical and horizontal integration) that allow for better linkages with urban and export markets and obtain higher prices for their output through improvements in quality and certification processes.

Table 2: Typology classes and examples of interventions

<table>
<tr><th>Typology class</th><th>Description</th><th>Examples of recommended innovations</th></tr>
<tr><td>Critical</td><td>High poverty, moderate potential</td><td>Long-term investments in agriculture such as funding R&D activities to generate technological changes and major investments in infrastructure.

Short-term assistance programs such as conditional cash transfers that incentivize human capital investments are recommended.</td></tr>
<tr><td>High priority</td><td>High poverty, medium/high potential, medium/moderate efficiency</td><td rowspan="3">Reduction in market access costs through road improvements and price information systems (ICTs).

Innovations that allow for improved access to inputs and extension services.

Innovative inclusive financial instruments to allow for savings of harvest income towards investments in next season’s production, credit for working capital, and insurance to mitigate risk of adopting new technologies

Strengthening of horizontal and vertical integration institutions that provide better access to markets to smallholders such as farmer groups and contract farming arrangements

Medium and small-scale productive infrastructure investments such as mini-irrigation projects and land management projects.</td></tr>
<tr><td>Medium priority with high agricultural opportunities</td><td>Medium poverty, medium/high potential, medium/moderate efficiency</td></tr>
<tr><td>Low priority with high agricultural opportunities</td><td>Moderate poverty, medium/high potential, medium/moderate efficiency</td></tr>
<tr><td>High performance</td><td>Moderate poverty, medium/high potential, high efficiency</td><td>Orientation to high values and export markets.

Certification and organic production to obtain higher premiums from agricultural production.

Increased financial inclusion to allow for higher returns on profit savings, credit to purchase additional land and expand farm and non-farm businesses.</td></tr>
</table>

4 Methodological approach

4.1 Model

In our setup, we do not only consider as agricultural innovations those paradigm-shifting technological changes that dramatically increase agricultural potential, but also the smaller innovations that allow smallholders to catch up to their peers and larger farmers by helping them overcome the specific challenges they face. Implicit in this setup, is the idea that there exists a maximum or optimum level farmers can catch up to with the smaller innovations of their own and their peers (and hence become more efficient), and an upper bound (which we call potential) that can be increased by larger investments in R&D with the support of governments, donors, and researchers. Hence, the approach needed to estimate the building blocks of our typology need to acknowledge this setup.

The two most commonly used methods to estimate the efficiency of production units are data envelopment analysis (DEA) (Charnes et al., 1978; 1981) and stochastic frontier analysis (SFA) (Aigner et al., 1977; Meussen and van den Broeck, 1977; Battese and Corra, 1977). DEA is a non-parametric approach that uses linear programming to identify the efficient frontier, while SFA is a parametric approach that hypothesizes a functional form and uses the data to econometrically estimate the parameters of that function.[4] Both methods measure efficiency as the distance between observed and maximum possible (frontier) outcomes, but the key advantage of SFA for our purposes is that, unlike DEA, it allows to separate random noise in the error term from the actual efficiency score. This is an important feature when analyzing agricultural activities, which are constantly exposed and extremely sensitive to (negative and positive) random shocks such as droughts, variation in international prices, etc. DEA estimates a deterministic frontier that incorporates the noise as part of the efficiency score, which is more appropriate when analyzing decision making units such as banks or factories rather than smallholder farms in developing countries. Hence, we prefer SFA for this study since it allows us to separate efficiency and random noise.[5]

The SFA approach allows the econometric exploration of the notion that, given the fixed local agroecological and economic conditions in a micro-region and the occurrence of random shocks that affect agricultural production (weather, prices, etc.), the investment, production decisions and technological innovations a farmer makes translate into higher or lower production and income. In such a context, inefficiency is defined as the loss incurred by operating away from the frontier given the current prices and fixed factors faced by the household. By estimating where the frontier lies, and how far each producer is from it, the

[4] See for example Park and Simar (1994), Kumbhakar and Tsionas (2008), and Martins-Filho and Yao (2015) for semi-parametric approaches to SFA estimation that relax some of its parametric functional form requirements.

[5] The main cost or disadvantage of using SFA is that it requires more detailed data to properly model the efficiency term and, as in any parametric approach, it relies on making the correct choice of functional form.

stochastic frontier approach helps to identify local potential and efficiency levels to construct the typology. A graphical depiction of this concept is shown in Figure 3.

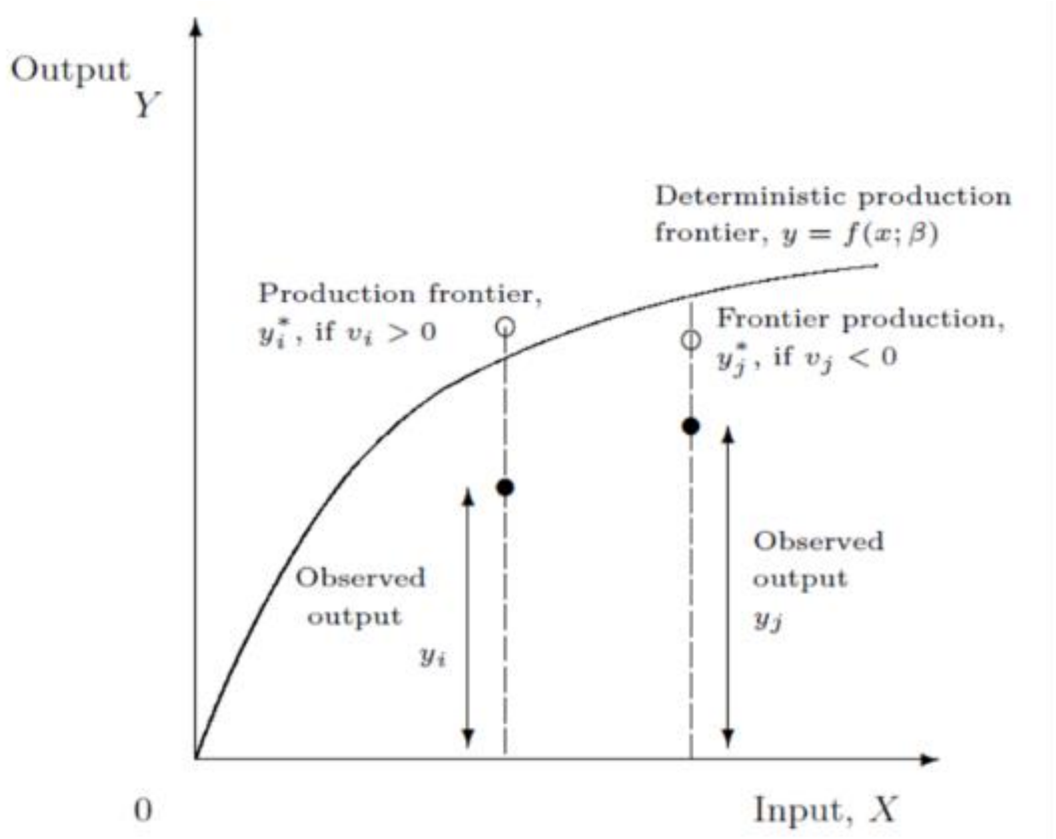

Figure 3: Stochastic production frontier in the single-output, single-input case

Using the basic model proposed by Aigner et al. (1977) and Meeusen & van den Broeck (1977) depicted in Figure 3, the stochastic frontier production function is defined as:

$$y_i = f(x_i;\beta)\exp(v_i - u_i) \quad (1)$$

where y_i is the possible production for farmer i,

$f(x_i;\beta)$ is an adequate function of inputs x and parameters β,

v_i is a random error with zero mean, associated with random factors that are not under the farmer's control, and

u_i is a non-negative random variable associated with factors that prevent farmer i from being efficient.

Then the possible production y_i is bounded by the stochastic quantity $f(x_i;\beta)\exp(v_i)$. It is assumed that the stochastic errors v_i are i.i.d. random variables distributed $N(0,\sigma^2)$, and independent from u_i. A farmer's technical efficiency is defined as the fraction of the frontier production that is achieved by his current production.

Given the frontier production of farmer i is $y_i^* = f(x_i;\beta)\exp(v_i)$ then his technical efficiency can be defined as:

$$TE_i = \frac{y_i}{y_i^*} = \frac{f(x_i;\beta)\exp(v_i - u_i)}{f(x_i;\beta)\exp(v_i)} = \exp(-u_i) \qquad (2)$$

Caudill & Ford (1993) and Caudill et al. (1995) showed that the presence of heteroskedasticity in u_i is particularly harmful because it introduces biases in the estimation of β and technical efficiency. This is very likely to occur if there exist sources of inefficiency related to factors specific fo the producer. In this case the distribution of u_i will not be the same for all the observations in the sample and a correction for heteroskedasticity needs to be made by modelling the variance of u_i:

$$\sigma_{u_i}^2 = \exp(z_i \delta) \qquad (3)$$

where z_i are farmer-specific factors affecting his or her technical efficiency.[6]

4.2 Estimation

To estimate the model expressed by equations (1)-(3) it is necessary to address the fact that farms are multi-output production units, making it necessary to move from a production function to a profit function approach.[7] The stochastic frontier profit function can be expressed as (Kumbhakar & Lovell, 2000):

$$\pi_i = f(p_i, w_i; \beta)\exp(v_i - u_i) \qquad (4)$$

where p_i and w_i are output and input price vectors, respectively.

In addition to the farm-specific factors affecting the farmer's technical efficiency, z_i, referred to in (3), in an agricultural context it is necessary to consider certain production factors that affect the farm's potential that cannot be easily modified in the short or medium term, such as climate and soil quality. For this reason, the farm's potential or frontier is adjusted using GIS data on agroecological zones or agricultural land use types. These variables are introduced as shifters of the deterministic portion of the frontier so (4) becomes:

$$\pi_i(p, w, AEZ) = f(p_i, w_i, AEZ_i; \beta)\exp(v_i - u_i) \qquad (5)$$

where AEZ are the agroecological zone variables.

[6] One of these farmer-specific factors particularly relevant to (the adoption of) agricultural innovations is risk aversion. Risk aversion, and the lack of mechanisms for many smallholders to deal with risk exposure (such as loss insurance), has a clear influence on a farmer's ability to be efficient and adopt new crops, practices, and technologies. Unfortunately, data on risk preferences is not available in the household surveys for most of the countries in this study, although it could be the subject of a country-specific study.

[7] In some cases, it will be necessary to move to a revenue frontier (instead of a profit one), since most surveys lack adequate data on smallholder farming costs, particularly input prices.

Assuming a Cobb-Douglas production function the normalized profit or revenue frontier function for the single output case estimated through maximum likelihood is:

$$\ln\frac{\pi}{p} = \delta_0 + \sum_n \delta_n \ln\frac{w_n}{p} + \sum_q \delta_q AEZ_q + v_\pi - u_\pi \quad (6)$$

To estimate equation (6) the typical data requirements are:[8]

- Household survey data for farm profits, producer level output and input prices, and farm and household characteristics.
- GIS data for local agroecological characteristics, such as land use, as well as for market access measures.

For each country, we restrict the survey sample to include only rural households involved in agriculture that engage in output marketing and report positive revenues. It is important to note that we do not value and incorporate the households' own consumption into agricultural revenues. The main reason for this is that we want our estimation to capture the difficulties smallholders face in accessing markets. If, for example, farmers are able to sell only a small amount of their output because they are facing severe efficiency bottlenecks, valorizing the unsold output and counting it as revenue would completely obscure this problem and make accessibility problems irrelevant.

Table 3 shows the effect of imposing the market orientation restriction to the survey sample sizes in each country. While for most countries in the study market-oriented farmers represent approximately 80% of the total number of farmers in the sample, an important fraction of the remainder 20% reports to be storing part of the harvest for sale at a future date. For Burkina Faso, where only 20% of the farmers report having sold any of their harvest, 98.5% of those who have not sold yet report still having most of their harvest in storage, and 40% of them have concrete plans to sell it soon. For Malawi, 43% of the farmers have not sold any of their harvest, but at least half of them reported to be storing part of their production for potential sales. While this raises concerns about the representativeness of the results based on the constrained samples, particularly for these two countries, it also indicates that this selection is partially caused by the timing of the surveys and the way they are rolled out, and not by inherent differences between farmers who report having sold already and farmers who have not. Including households that reported no agricultural income in the estimation sample would also present a few methodological challenges.[9] Ultimately, it should be acknowledged

[8] In an ideal setup, data from a recent agricultural census would also be used to extrapolate regional estimates using the survey level parameters and census level regional means.

[9] When estimating profit or revenue models, SFA employs semi-flexible functional forms such as the log or translog functions that facilitate convergence when maximizing the likelihood function (Berger and Mester, 1997). Since it is not possible to take the logarithm of a non-strictly positive value, the most common way to address zeroes or negatives in the dependent variable of a SFA estimation has been to add a positive constant to its unlogged value (Berger and Mester, 1997, Vander Vennet, 2002, Maudos et al., 2002). However, as Bos and Koetter (2011) point out, this manipulation can have undesired effects on the error term structure, which is particularly problematic in SFA, given the outcome of interest is the composition of total error, rather than coefficient estimates or marginal effects.

that the route we take in this study (truncating the estimation sample to positive revenue values) has a minimal effect on the determination of the agricultural revenue potential (which should be more influenced by the more successful market engaged farmers), but could result in an overall upward bias in the agricultural efficiency estimates, and biased estimates of the coefficients in the technical inefficiency heteroskedasticity correction estimation.

Table 3: Survey samples constraints

	Households in the full survey sample	Households engaged in agriculture	Households reporting agricultural revenue	(3) / (2)
	(1)	(2)	(3)	(4)
Burkina Faso	10,441	7,347	1,489	0.203
Ethiopia	4,954	3,592	2,786	0.776
Ghana	16,772	9,100	7,262	0.798
Kenya	13,158	7,548	6,049	0.801
Malawi	12,271	10,165	5,822	0.573
Nigeria	4,582	2,842	2,162	0.761
Togo	5,532	3,521	2,739	0.778
Zambia	19,397	9,870	7,865	0.797

Source: IFPRI

Table 4 illustrates the frontier estimation results for the case of Burkina Faso.[10] The deterministic portion of the agricultural revenue frontier is determined by the prices[11] of the main crops produced by the households in the sample, and the GIS AEZ variables. An increase in the price of a crop or the area in a specific land use type with a coefficient with a positive and significant sign is associated with higher agricultural revenue potential. The second half of the table reports the results of the heteroskedasticity correction of the variance of the technical inefficiency error term. Because this term is non-negative, a positive value for the coefficient of any of these variables indicates an increase in value associated with a decrease in inefficiency (or increase in efficiency). For example, in the case of Burkina Faso an increase in the landholding of a farmer is linked with decreased inefficiency, which reflects that better access to land allows farmers to adjust to market conditions (by having more freedom to choose at what scale to operate) and be more efficient. Under perfect land and credit market conditions, farmers could adjust their scale by either selling, buying, renting in, or renting out land and land size would not be a significant factor in determining efficiency.

[10] SFA estimations for the other seven countries are included in Appendix 1.

[11] For the estimation, we normalize and take the logarithm of all the prices and variables expressed in monetary term.

With the estimation approach described above, parameter estimates are obtained that allow for the prediction and extrapolation of agricultural income potential and efficiency measures at the regional level, which can then be grouped and classified into types to construct the typology. The typology then allows the identification of types of regions with extremely different needs, bottlenecks and opportunities, which in turn will result in a different set of investment recommendations for development in each type of region, including decisions regarding investments in agricultural innovation.

4.3 GIS data and accessibility model

One of the factors z_i influencing efficiency in Equation (3) is the degree of market accessibility each region has. For this purpose, IFPRI has estimated an accessibility model for each of the 12 PARI countries to determine what are the time costs of accessing the closest market from any point in a country's territory, where "market" is defined as actual markets to trade agricultural outputs, or as towns or cities of certain size that generate high levels of demand for those products. To calculate this model, global geographic data on water, roads, railroads, topography, and natural barriers publicly available from DIVA-GIS is used. GIS land cover type data from NASA and the USGS is also used as an explanatory variable in the stochastic frontier estimation.

4.4 Typology construction

It is worth noting that the classification above is one of several ways to classify the different elements of the typology into types. For this study, we will focus on a method for categorizing poverty, potential, and efficiency into moderate/medium/high classes known as "*natural"* breaks.[12] The natural breaks approach uses Jenks Natural Breaks algorithm[13], which, similarly to cluster analysis methods, minimizes differences within classes, and maximizes them across classes. This approach reduces the arbitrariness in the positioning of the cutoffs between classes, by finding "natural" breaking points that preserve clusters of "similar" units. Thus, the category groups generated by the natural breaks approach can be very uneven, and the resulting typology map can have fewer classes or some classes with very few regions, but it is a more natural reflection of the underlying data.

[12] The tercile breaks approach is an alternative method that splits the distribution (at the lowest tier administrative level) of the three typology variables (potential, efficiency, and poverty) at the 33rd and 67th percentiles, effectively creating three categories (moderate, medium, and high). Classifications and maps constructed under the tercile breaks approach are available from the authors upon request.

[13] See de Smith et al. (2015).

Table 4: Burkina Faso: Agricultural revenue SFA estimation

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Sorghum	0.261	0.379
Maize	0.153	0.181
Cowpea	0.310	0.171*
Sesame	0.450	0.136***
Cotton	0.392	0.249
Land Use		
Shrublands	-6.073	1.317***
Savannas and Urban	0.886	0.417**
Grasslands and Barren	-0.908	0.235***
Croplands	0.713	3.114
Constant	5.600	0.334***
$ln\sigma_v$		
Constant	0.715	0.046***
$ln\sigma_u^2$		
Land	-0.349	0.077***
Log farm assets	-0.285	0.051***
Household size	-0.062	0.033*
Time to Market	0.019	0.175
Female Head	0.255	0.189
Maximum Schooling	0.028	0.032
Constant	2.686	0.327***
σ_v	1.429	0.033
N		1,489
chi2		237.79

5 Results

In this section, we present the results and typology maps for Burkina Faso[14], Ethiopia, Ghana, Kenya, Malawi, Nigeria, Togo, and Zambia, with additional maps on market accessibility for each country presented in Appendix 2. Auxiliary maps from the eAtlas are also included to further explain the typology results.[15] High resolution versions of the maps (including shapefiles) are also available for download on the eAtlas (http://eatlas.resakss.org)

5.1 Burkina Faso

The data sources used for the estimations and mapping for Burkina Faso are:

- Household survey: *Enquete Multisectorielle Continue* 2013/14, publicly available through the World Bank Microdata Catalog. It has a sample of 10,860 households, out of which 1,489 are used for the frontier estimation, and is representative at the national, regional, and urban/rural levels. As mentioned before, the survey does not include information on livestock and its by-products.
- Poverty data: 2014 UNDP report *Carogtaphie de la Pauvrete et des Inegalites au Burkina Faso*.

The agricultural potential map generated by the frontier estimation for Burkina Faso (Figure 4) shows a clear north – south divide. The low agricultural potential in the north of the country results from unfavorable conditions for agriculture: predominance of shrubs, savanna and steppe, characterized by rocky soils, and a short wet season that produces an average of 300 – 400 mm of rain per year. In contrast, the south received more than 750 mm of rain in 2013 (Figure 5).

The agricultural efficiency map (Figure 6) shows instead an east – west divide, with higher efficiency regions appearing more often in the western side of the country. Combining potential and efficiency into a single map by estimating the unrealized agricultural potential (Figure 7) helps to illustrate the existing potential yet to be attained in each region (i.e., the size of the potential or frontier gap). As expected from the patterns in the potential and efficiency maps, the unrealized potential measure follows closely the north – south pattern of the potential map, with larger potential gaps being found in the south of Burkina Faso, except for the southwestern region where the high potential opportunities are offset by the high efficiency levels. The combination of high agricultural potential in the south and high

[14] Because of the questionnaire design of the household survey used for Burkina Faso, revenues from livestock activities are not included in its frontier analysis and typology maps.

[15] The years for the eAtlas maps are chosen to match as best as possible the year of each country's household survey used for the analysis.

agricultural efficiency in the west is also consistent with the production patterns of major crops such as maize and rice (Figure 8 and Figure 9).

The poverty map for Burkina Faso (Figure 10) shows a more heterogeneous picture than the agricultural maps, with a less obvious geographical pattern, but with lower poverty areas concentrated in the regions of Boucle du Mouhoun, Cascades, and Hauts-Bassins in the west. It is extremely interesting to note also that the poorest area of the country, the south-eastern section of the Est region, is also a high (unrealized) potential area which indicates the opportunity to reduce poverty through efficiency enhancing investments in agriculture in the region.

Combining the potential, efficiency, and poverty estimates results in the agricultural typology shown in Figure 11. The predominance of red (critical with moderate agricultural potential) and orange (medium priority with moderate agricultural opportunities) areas in the north of the country is consistent with the above average poverty rates and the poorer agroecological conditions. While animal husbandry plays an important role in providing a source of livelihood for rural households in this region, livestock activities were not included in the analysis for Burkina Faso because of data limitations. Moving south to the Sub-Sahelian zone encompassing the central and north central areas of the country, the map colors shift to light green indicating better opportunities for agriculture (higher potential). Sorghum and millet are two of the more important crops in this region, which is damper than the northern parts of the country. This is also an area of higher population density, with more income generating opportunities beyond agriculture. Still, the dark green regions in the southern half of the country reveal pockets of high poverty areas with agricultural potential gaps that can be targeted to improve living conditions of rural households in these areas.

Following the rationale described in Section 0, we can define two types of innovations: efficiency enhancing and potential enhancing. Efficiency enhancing innovations help farmers overcome bottlenecks in agricultural production and marketing in the short term, by affecting those factors they can control. For example, improved farming and land management practices, or access to existing technologies and knowledge, are context-specific innovations that can help close efficiency gaps and let farmers falling behind catch up with those operating closer to their maximum potential (frontier). Potential enhancing innovations, which are aimed at shifting the current production frontier, usually tackle inefficiencies in stages of the production and marketing process beyond the direct control of the farmer, and tend to yield benefits in the longer term. This would involve R&D investments in new technologies, seeds, and fertilizers, better adapted to specific contexts, large scale improvements of the transportation network to reduce transaction costs and prices at the local, regional, and national levels, etc.

Regions that would be a better target for efficiency enhancing innovations are areas that have high potential and low efficiency (areas with high unrealized potential such as dark green areas). The large efficiency gaps in these areas make them ideal for the implementation of agricultural innovations and investments in rural development that help these areas reach their maximum potential. Areas with low agricultural potential and above average poverty rates (such as red areas) require instead different investments in rural development, focused in increasing the overall farming potential of the region before increasing efficiency. Consistent with our discussion of the typology map results, potential enhancing innovations are most needed in the north of the country, where conditions for agriculture are less favorable, while efficiency enhancing innovations would yield greater returns in the center and south, where the agricultural potential gaps are large.

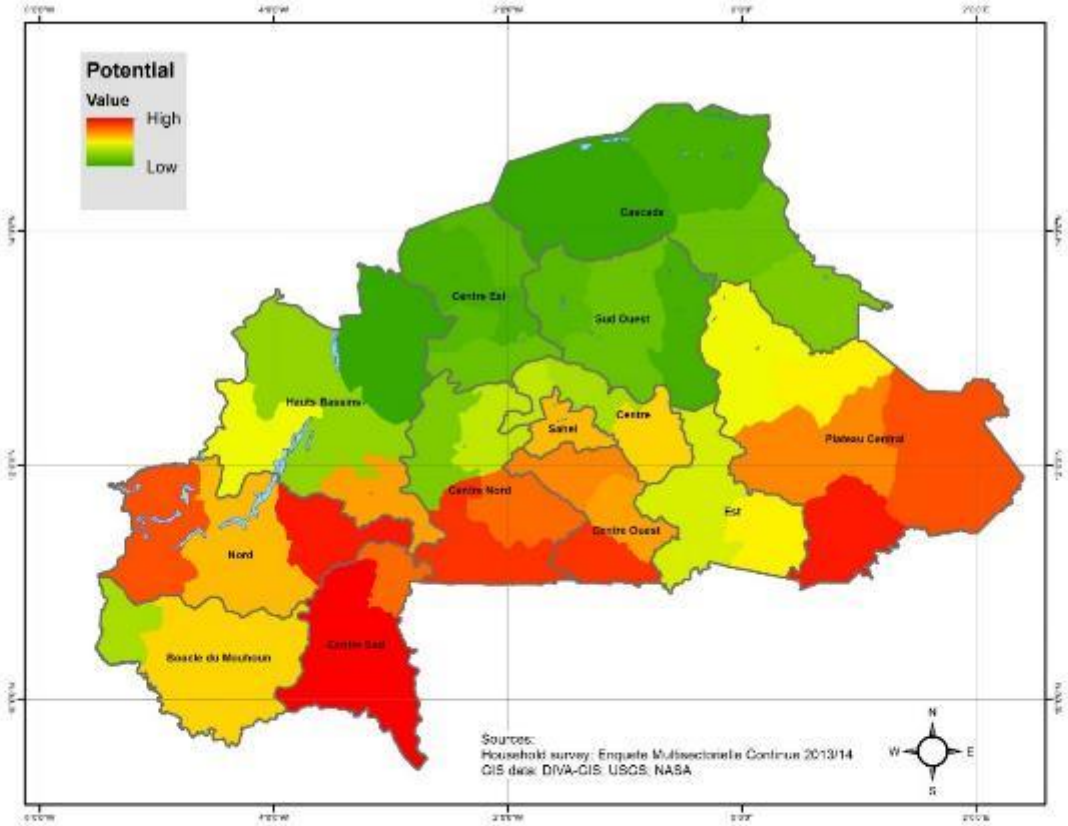

Figure 4: Burkina Faso: Agricultural potential

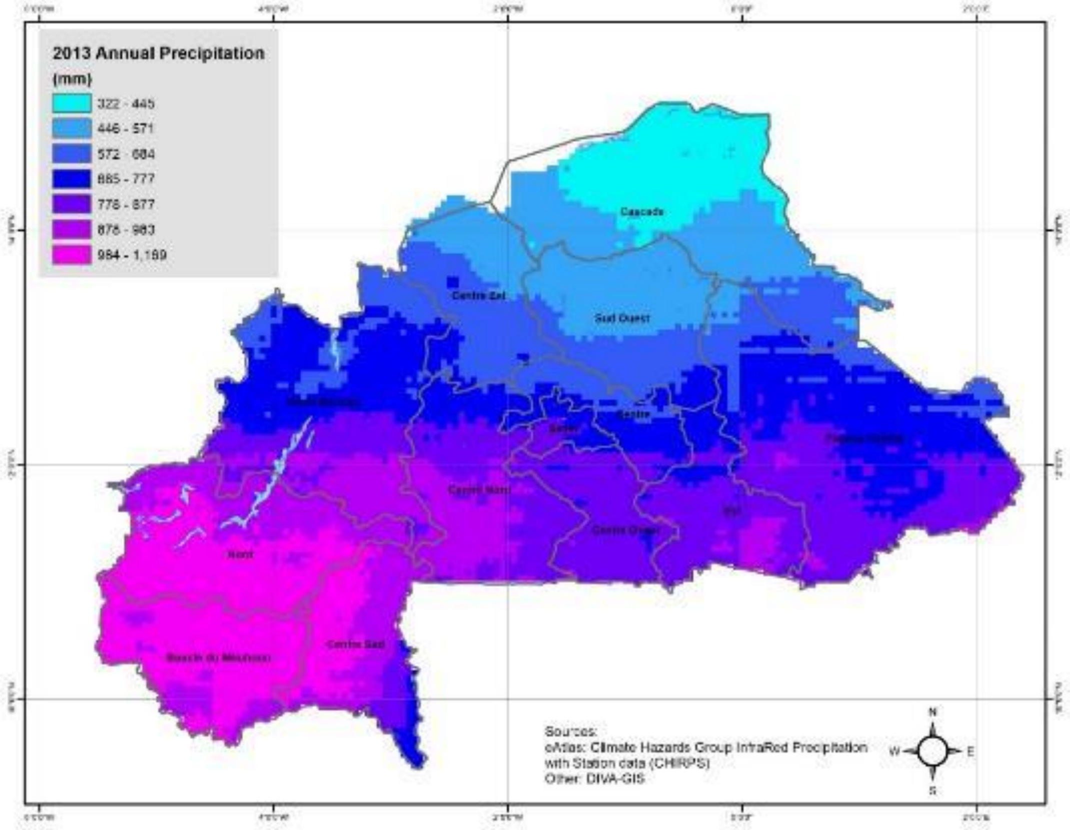

Figure 5: Burkina Faso: Annual precipitation (mm), 2013

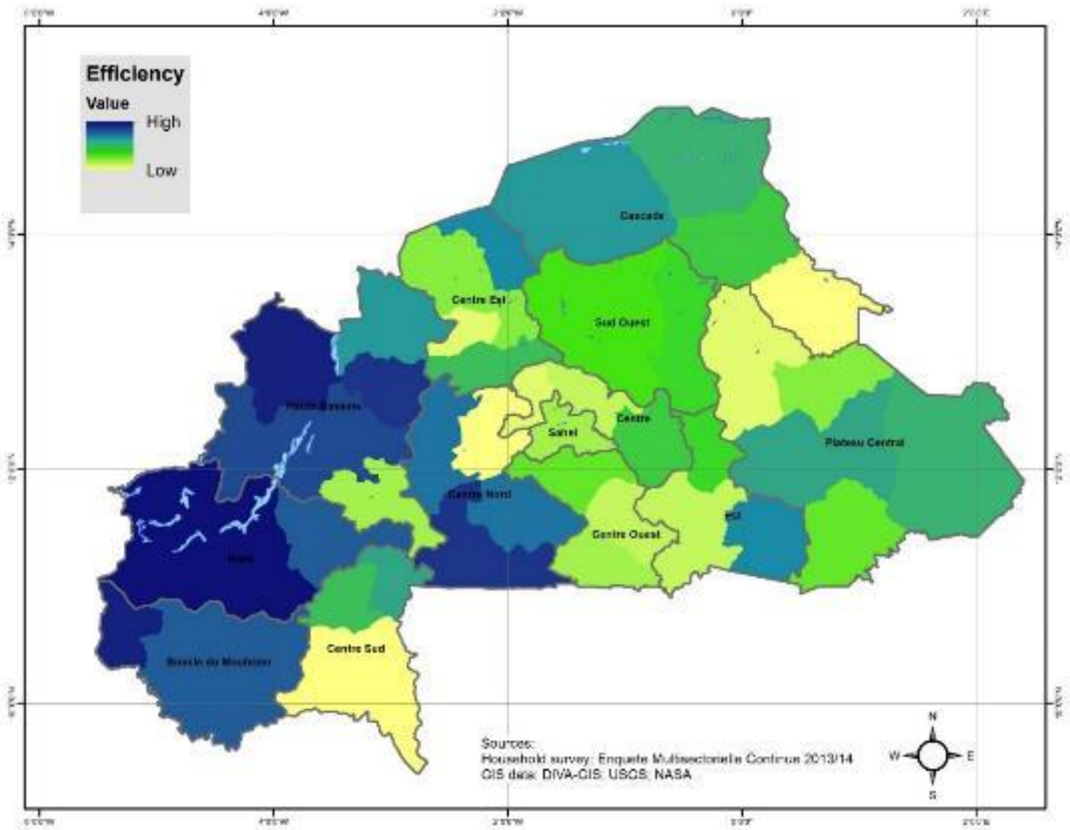

Figure 6: Burkina Faso: Agricultural efficiency

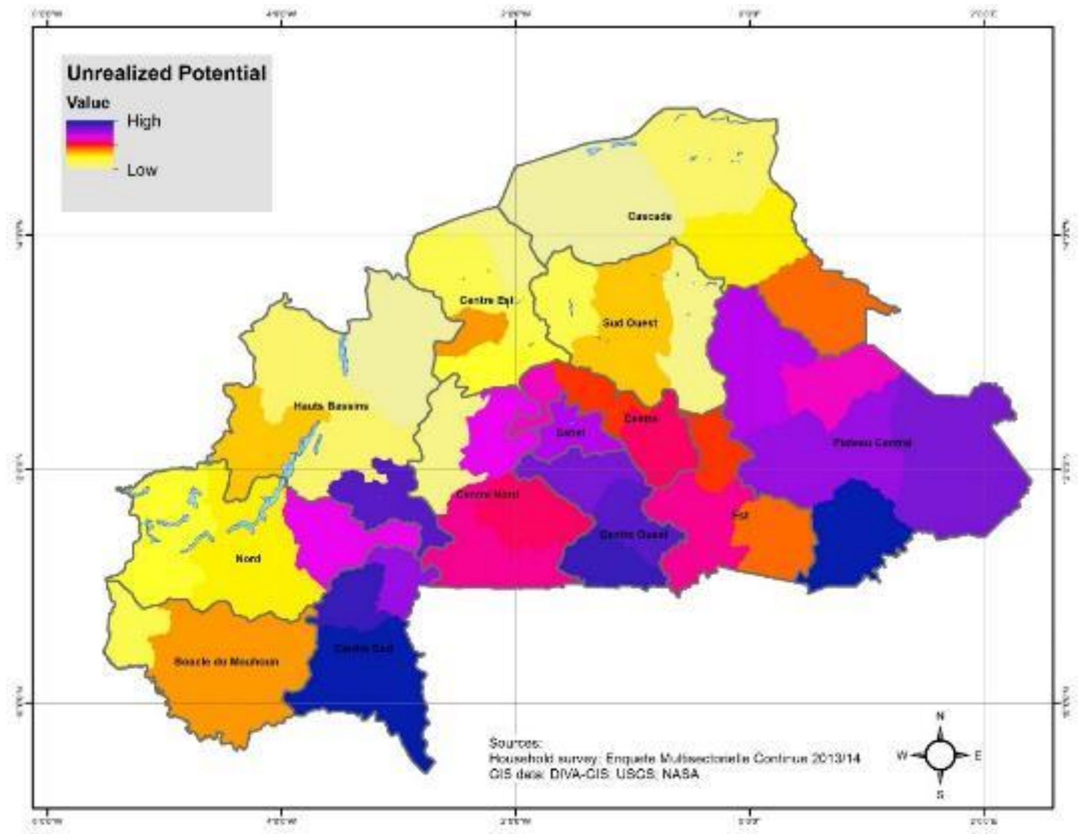

Figure 7: Burkina Faso: Unrealized agricultural potential

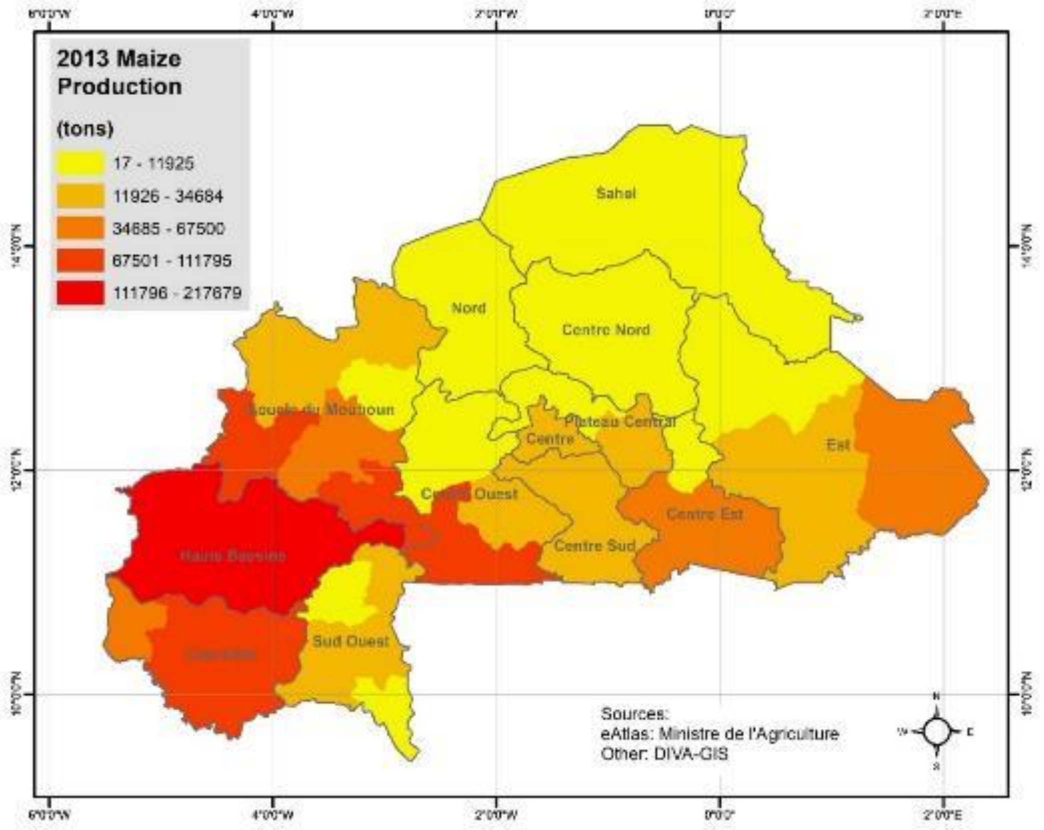

Figure 8: Burkina Faso: Maize production (Tons), 2013

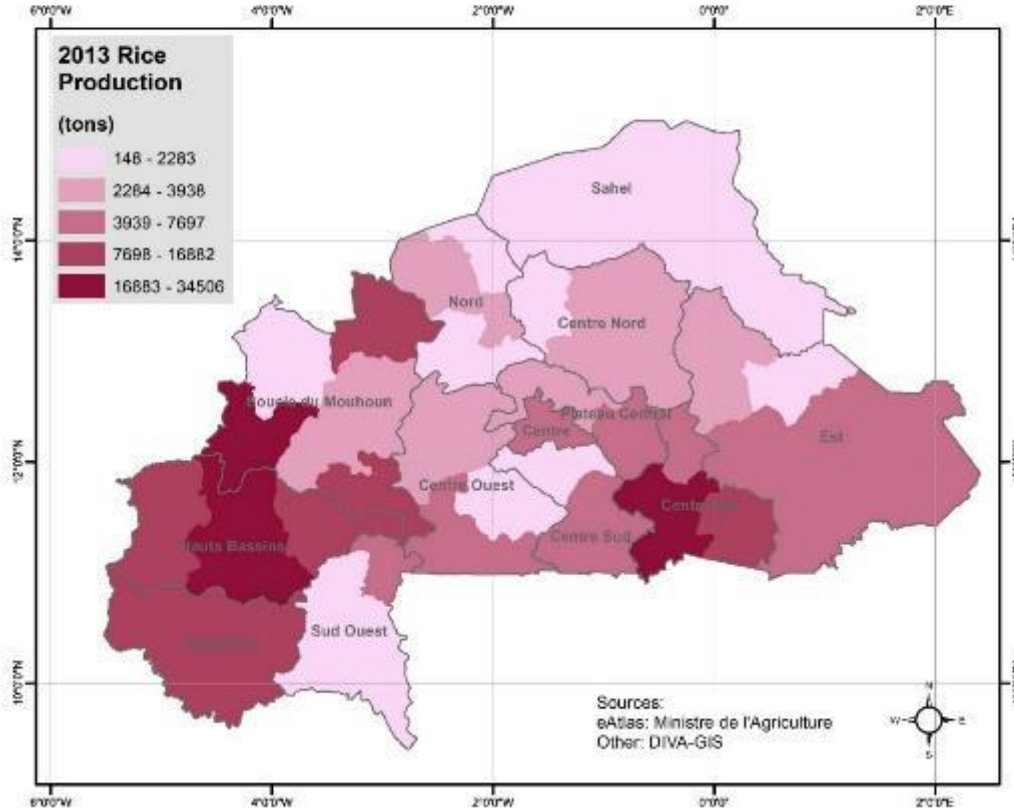

Figure 9: Burkina Faso: Rice production (tons), 2013

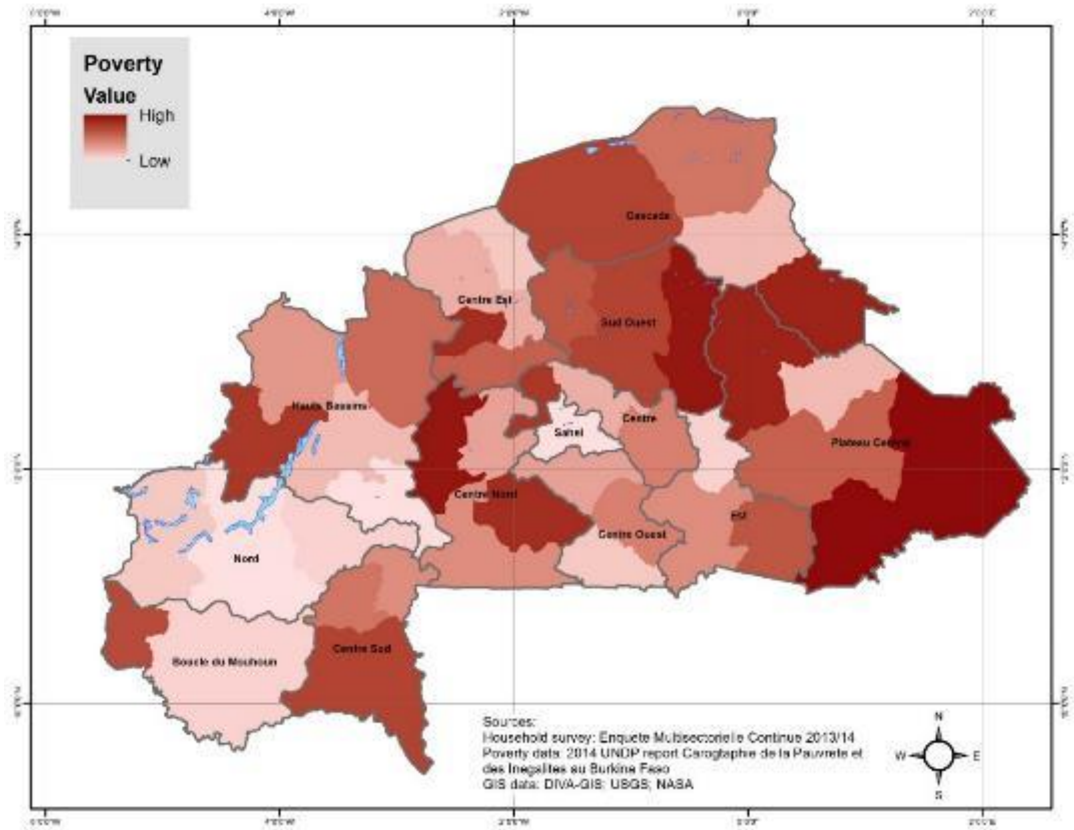

Figure 10: Burkina Faso: Poverty map

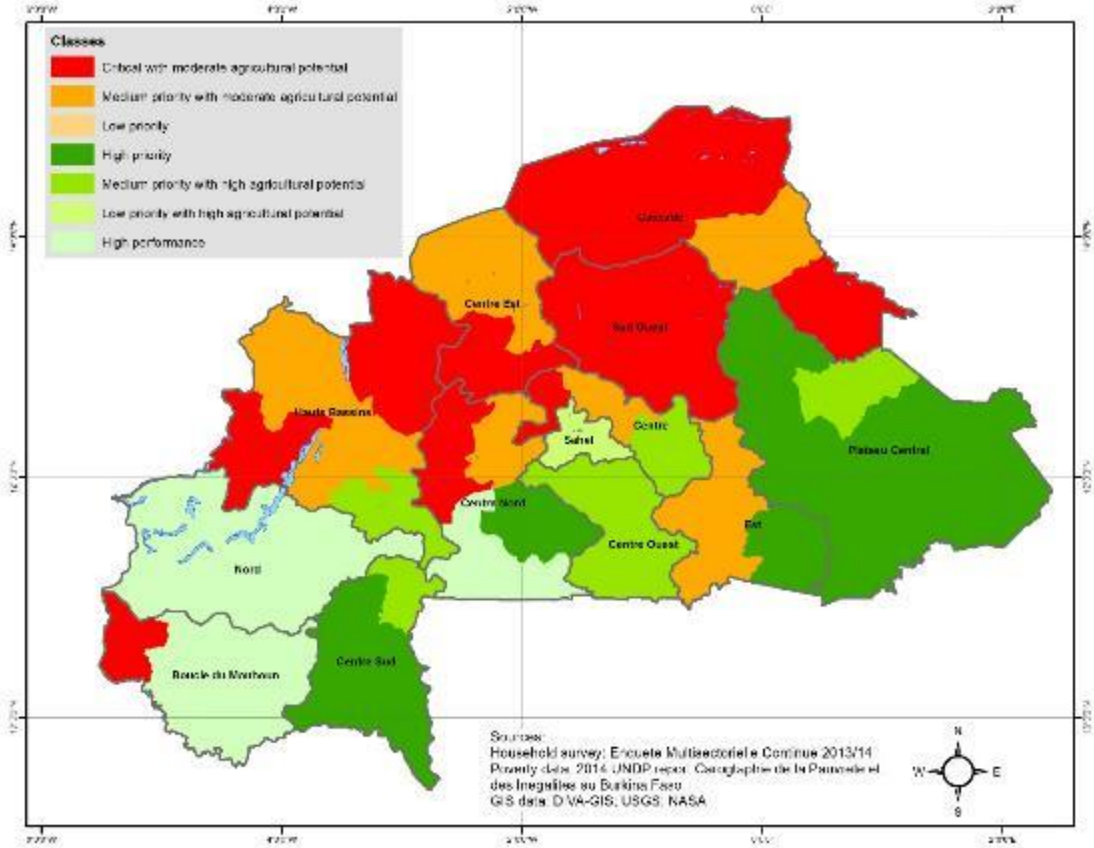

Figure 11: Burkina Faso: Agricultural typology

5.2 Ethiopia

The data sources used for the estimations and mapping for Ethiopia are:

- Household survey: The Ethiopia Socioeconomic Survey Wave Three 2015/16, publicly available through the World Bank Microdata Catalog. It has a sample of 4,954 households, out of which 2,786 are used for the frontier estimation, and is representative at the national and urban/rural levels.
- Poverty data: Oxford Poverty and Health Development Initiative.

Ethiopia's geography is characterized by mountains running from north to south, separated by the Rift Valley running southwest to northeast, and by the lowlands in the Northeast and south-western portions of the country. Rainfall is also generally correlated with altitude, with higher elevations receiving much more precipitation than lowlands. Regions above 1,500 meters receive above 900 mm annually while lower lying areas average receive below 600 mm (Figure 12). The exception to this is the western most portions of the country where the lowlands do receive substantial rainfall, which explains the lower poverty rates and higher agricultural potential in the area (Figure 13 and Figure 14). While not well suited for crop farming due to limited rainfall, the northern half of the Afar region shows high potential while some areas in the Somali region show medium potential levels due to the importance of animal husbandry in this part of the country. In both regions, livestock revenue makes up 85% and 93% of farm revenue respectively, compared to an average of approximately 50% in the rest of the country.

The regional efficiency levels (Figure 15) combined with the agricultural potential determine the location of the largest potential gaps (Figure 16). The areas with the highest unrealized potential levels can be found in Afar and Benishangul-Gumaz.

The typology map (Figure 17) shows that most regions of the country are considered high priority (dark green) and critical (red) areas. The natural breaks approach finds that the differences in poverty levels across regions are too small to separate them and classifies most of the country in the high poverty class, except for Tigray and Gambela. The high priority regions would benefit the most from efficiency enhancing innovations, due to their high poverty rates and large potential gaps.

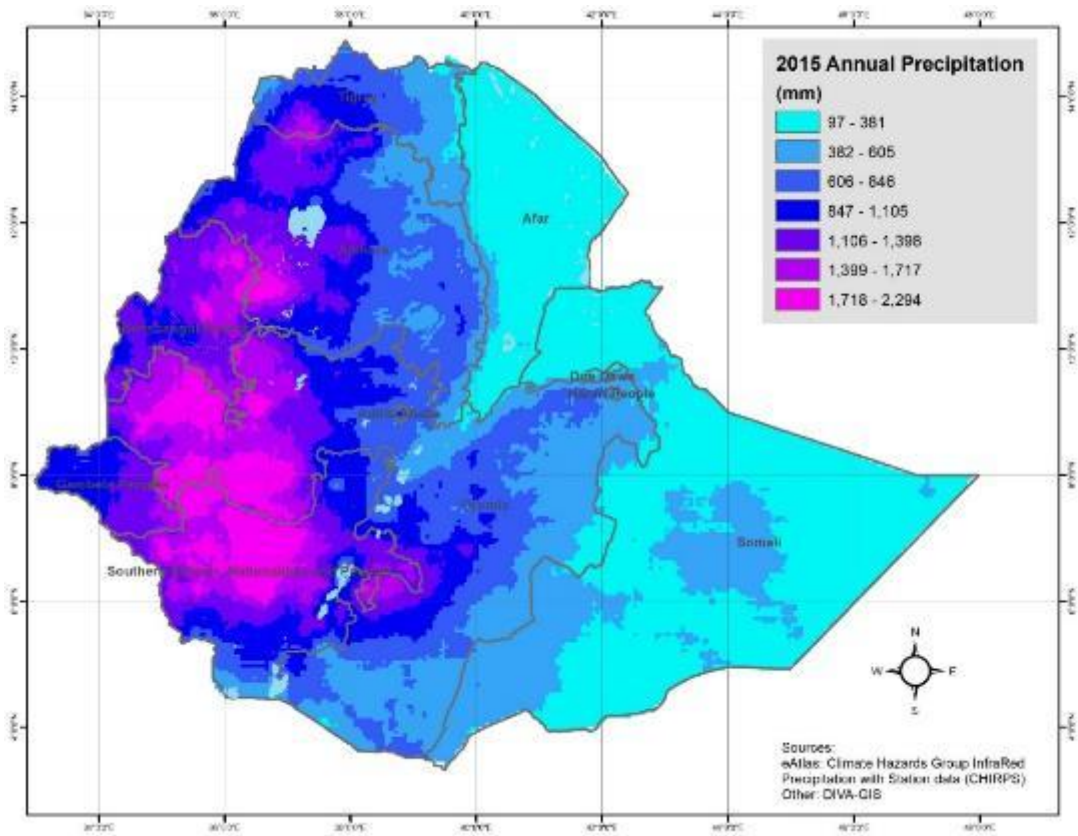

Figure 12: Ethiopia: Annual precipitation (mm), 2015

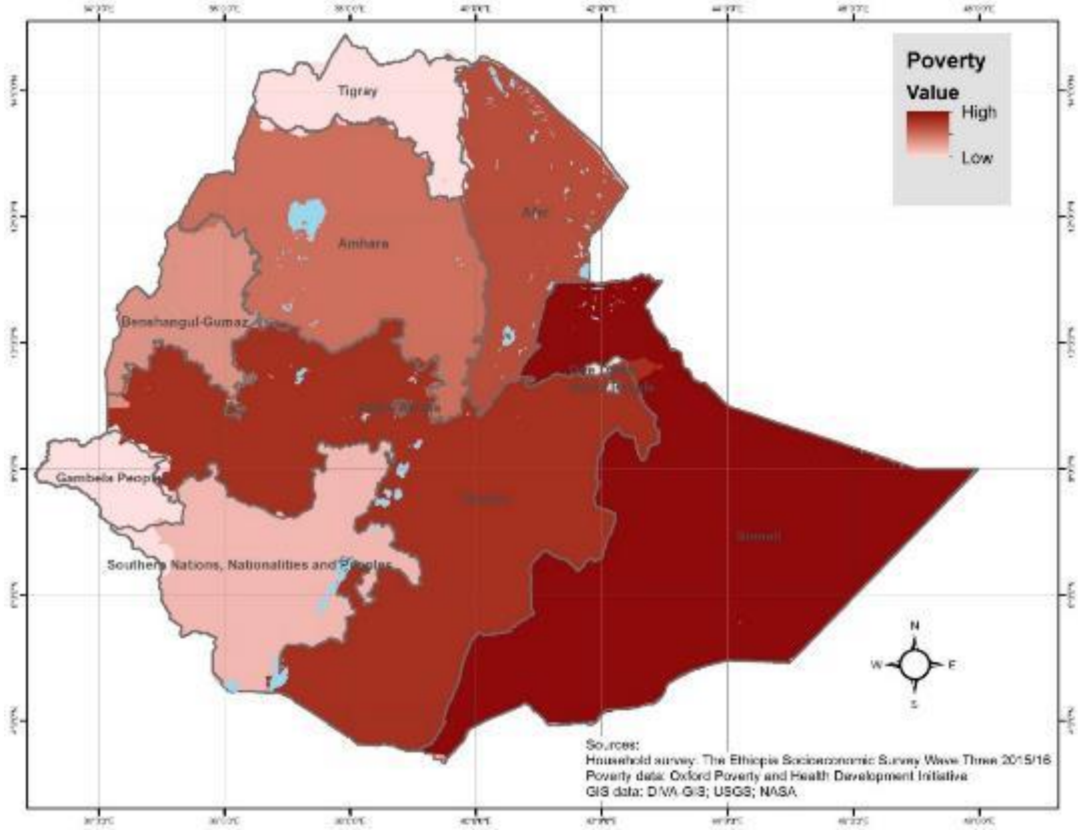

Figure 13: Ethiopia: Poverty map

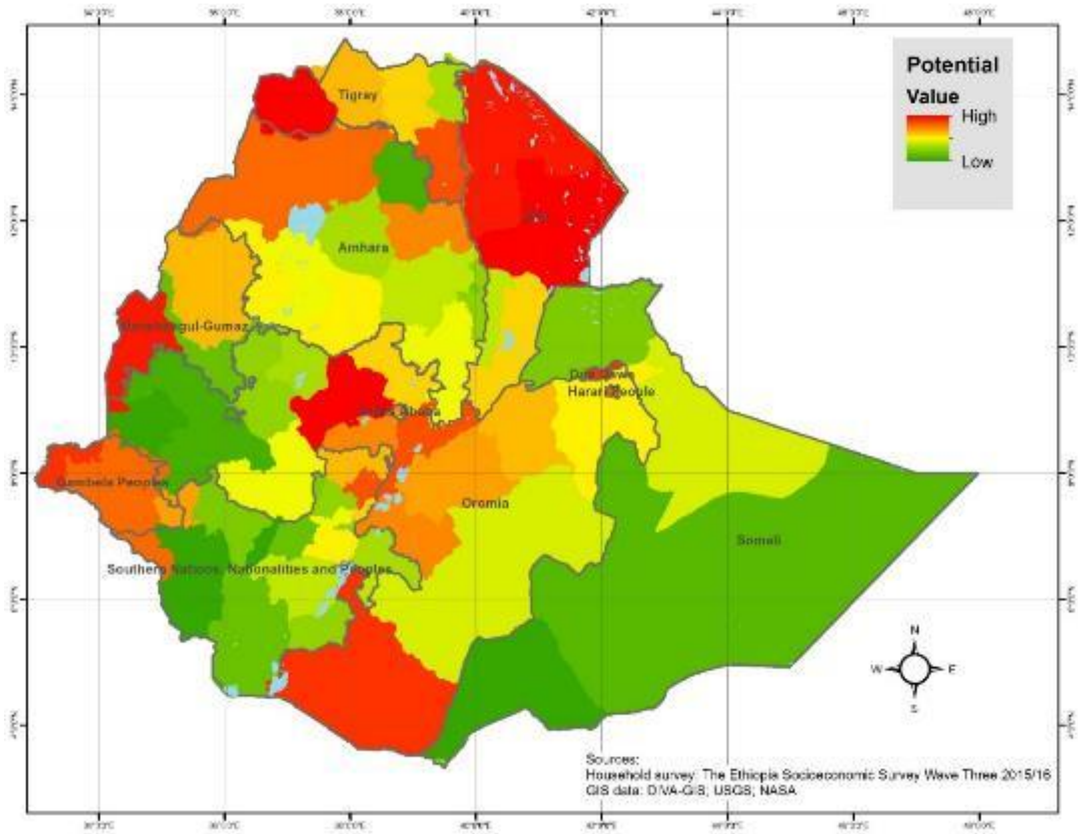

Figure 14: Ethiopia: Agricultural potential

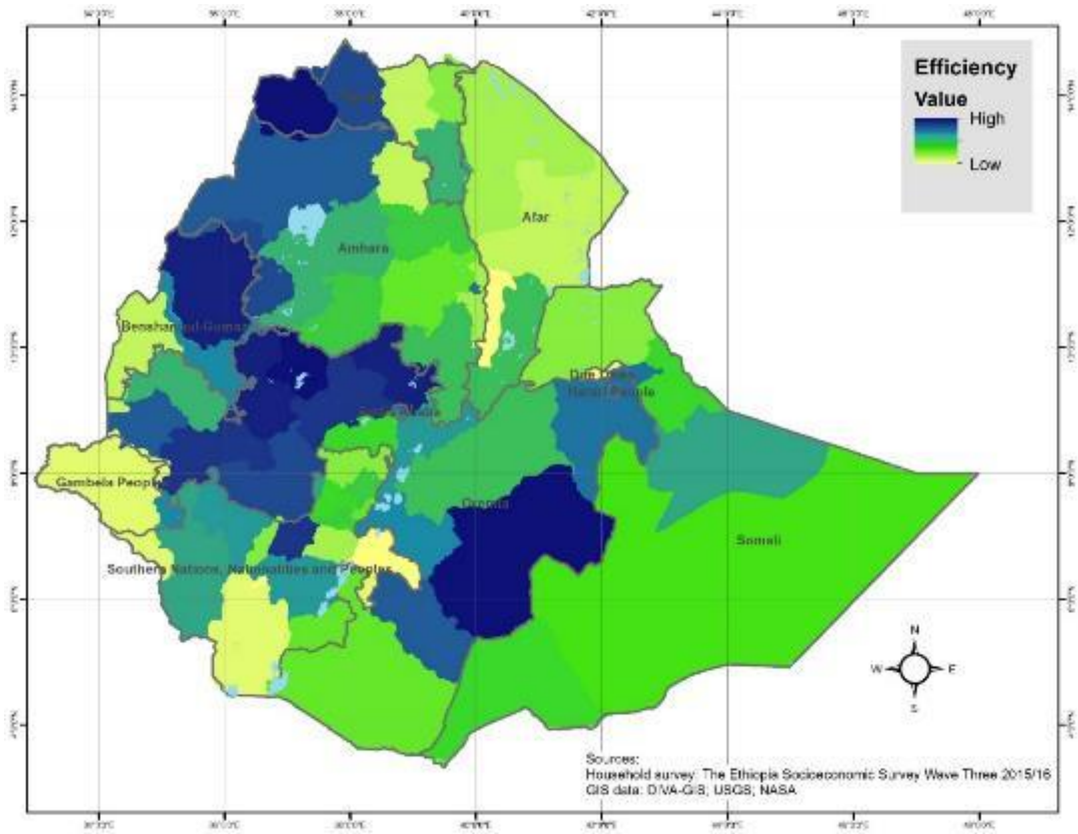

Figure 15: Ethiopia: Agricultural efficiency

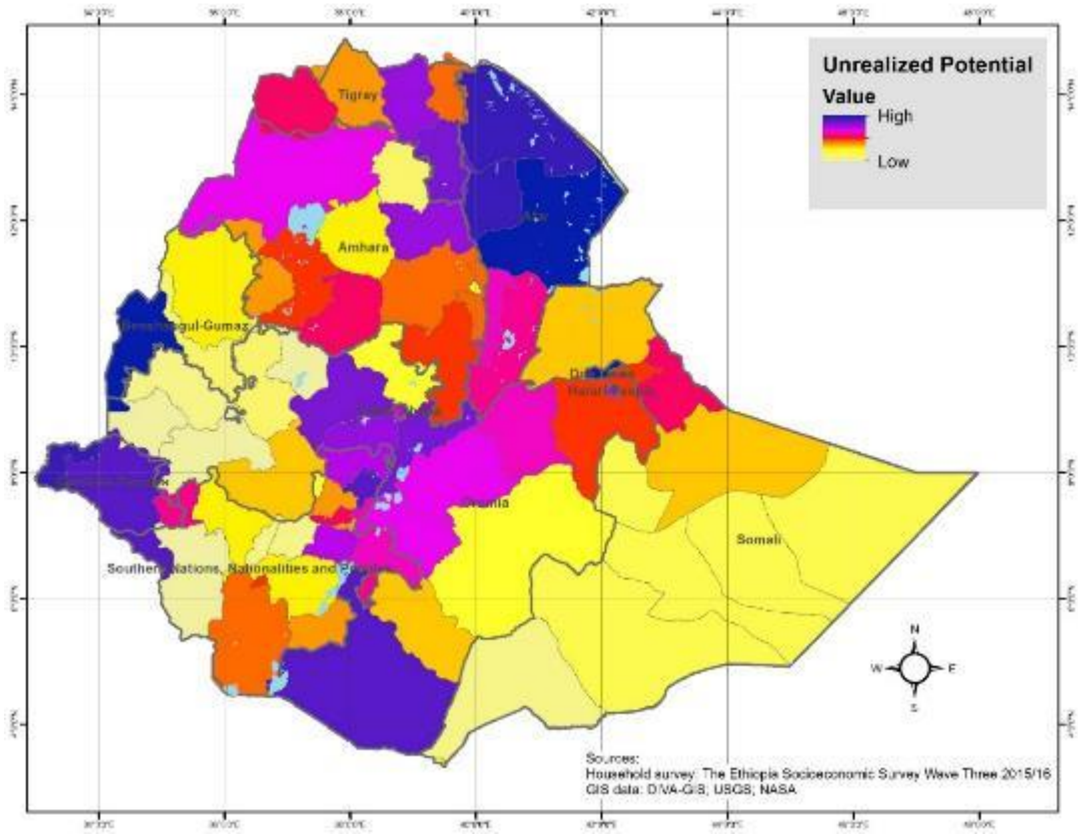

Figure 16: Ethiopia: Unrealized agricultural potential

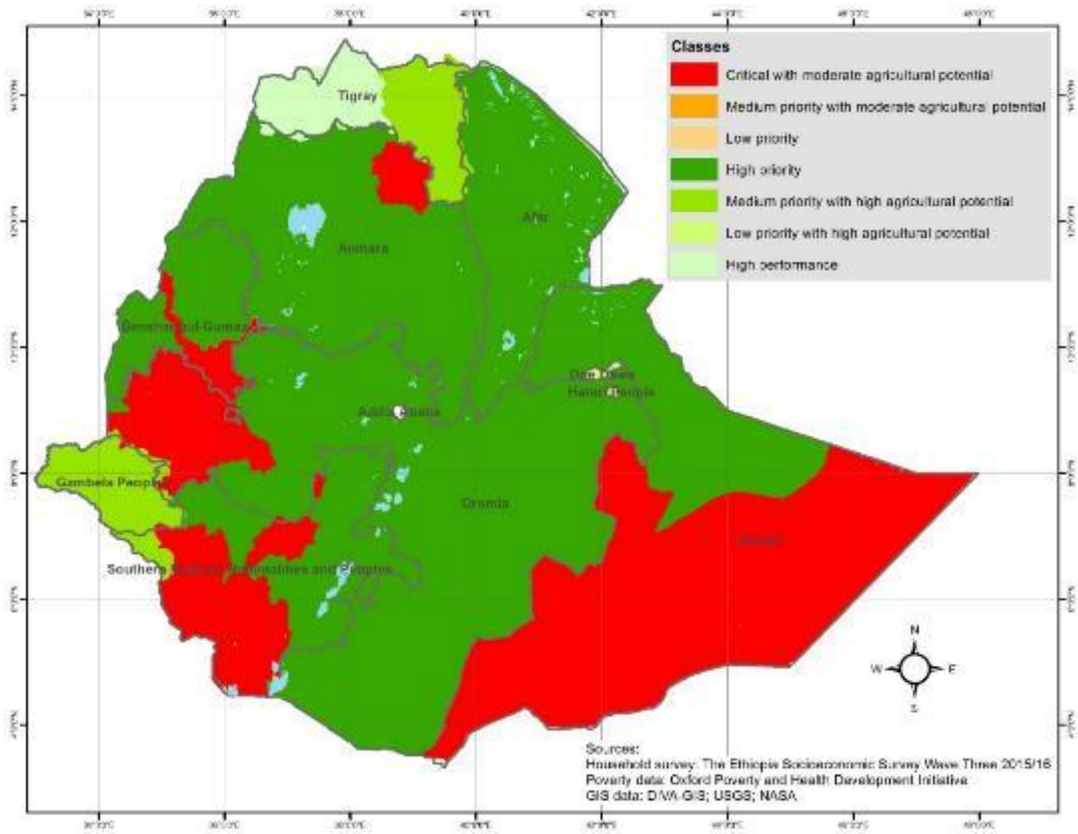

Figure 17: Ethiopia: Agricultural typology

5.3 Ghana

The data sources used for the estimations and mapping for Ghana are:

- Household survey: The Ghana Living Standards Survey 6 2012/2013, available through the Ghana Statistical Service and the World Bank. It has a sample of 16,772 households, out of which 7,262 are used for the frontier estimation, and is representative at the national and regional levels.
- Poverty data: Ghana Poverty Mapping Report from the Ghana Statistical Service (2015).

Agricultural practices in Ghana are largely determined by rainfall patterns (Figure 18), which increases moving from north to south with the northern regions receiving less than 1,100 mm annually and the southern portions receiving over 2,000 mm. The exception to this is the south-eastern coast, which is one of the driest areas of the country receiving on average of 750 mm per year. The agricultural potential map in Figure 19 reflects this pattern well with the lower potential areas in the north and the high potential areas, with a few exceptions, in the southwest. The area around the Volta Lake region, while offering an additional water source in some of the drier portions of the country has generally poor soil quality. However, the northern region also has abundant grassland which helps explain the cluster of high and medium potential regions scattered through the upper portion of the Volta Lake due to the potential for livestock production.

The agricultural efficiency map on the left panel of Figure 21 shows pockets of high efficiency concentrated in the northeast and southwest of the country. A clearer pattern emerges once this efficiency map is combined with the potential map, as shown on Figure 20. The unrealized agricultural potential map (Figure 21) shows the current potential yet to be attained in each region (i.e., inefficiency × agricultural potential, where inefficiency = 1 - efficiency). The high efficiency areas in the northeast are also low potential regions, and therefore leave little potential left to be exploited without frontier shifting innovations. Medium to high unrealized potential opportunities emerge in the central areas of the country due to the combination of medium agricultural efficiency and potential. And for most of the southern regions of Ghana, but particularly for the south west, the high levels of agricultural potential make efficiency-oriented innovation investments attractive regardless of the current levels of efficiency.

The poverty map in Figure 22 reveals a pattern that is the mirror opposite of the agricultural potential map, with poverty rates increasing from south to north, and particularly towards the northwest.

The combination of the potential, efficiency, and poverty dimensions results in the agricultural typology shown in Figure 23. The typology map displays and expands the patterns from the previous maps, showing most of the better off areas (high performance class in light green) in the cocoa producing region of the south west, and more pockets of high poverty regions appearing moving north (shaded in dark green and red depending on the level of unrealized agricultural potential). Following these patterns, efficiency enhancing innovations are better suited for the south of the country, while potential enhancing innovations are ideal for the northwest and the poor soil quality areas around the Volta Lake.

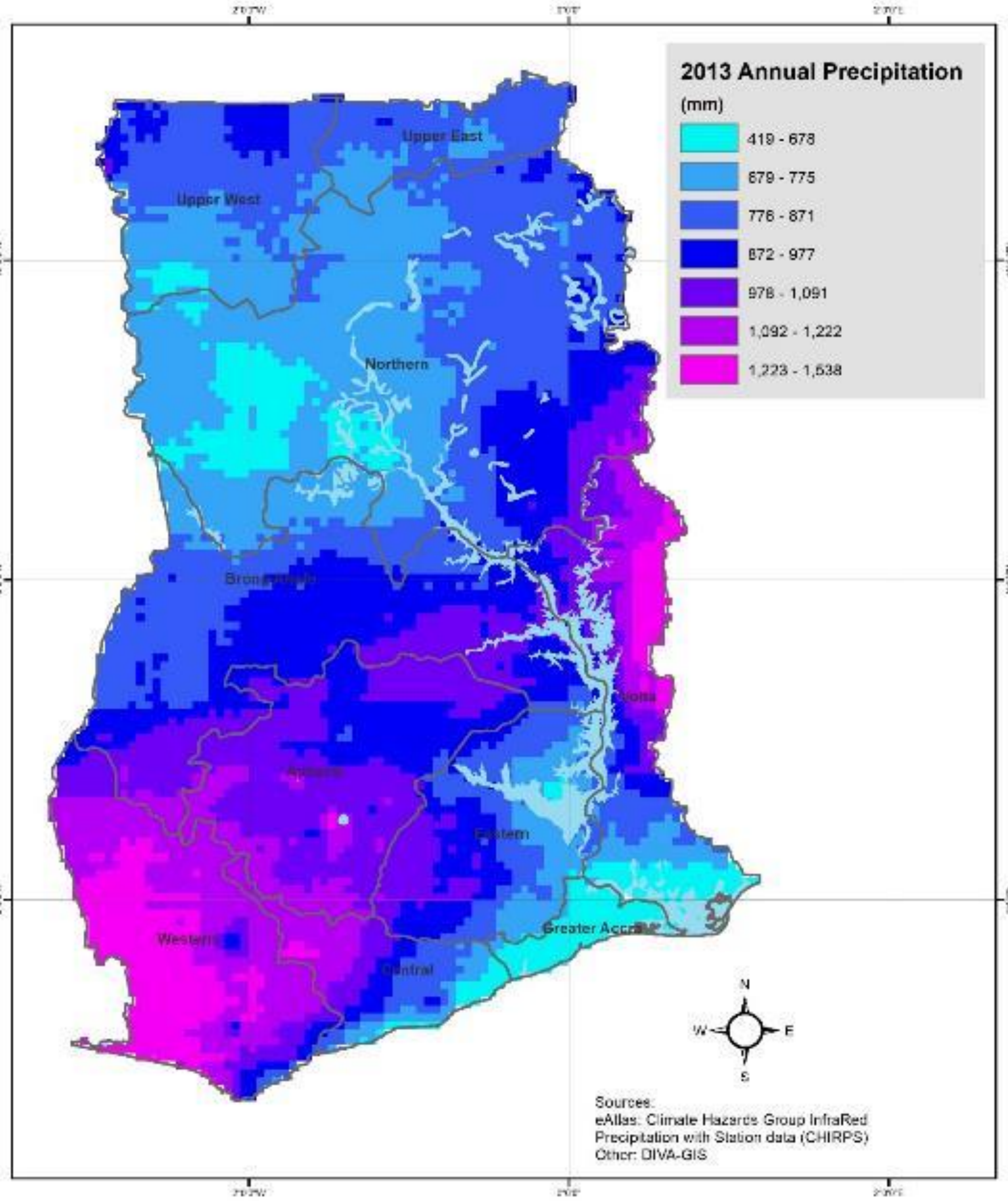

Figure 18: Ghana: Annual precipitation (mm), 2013

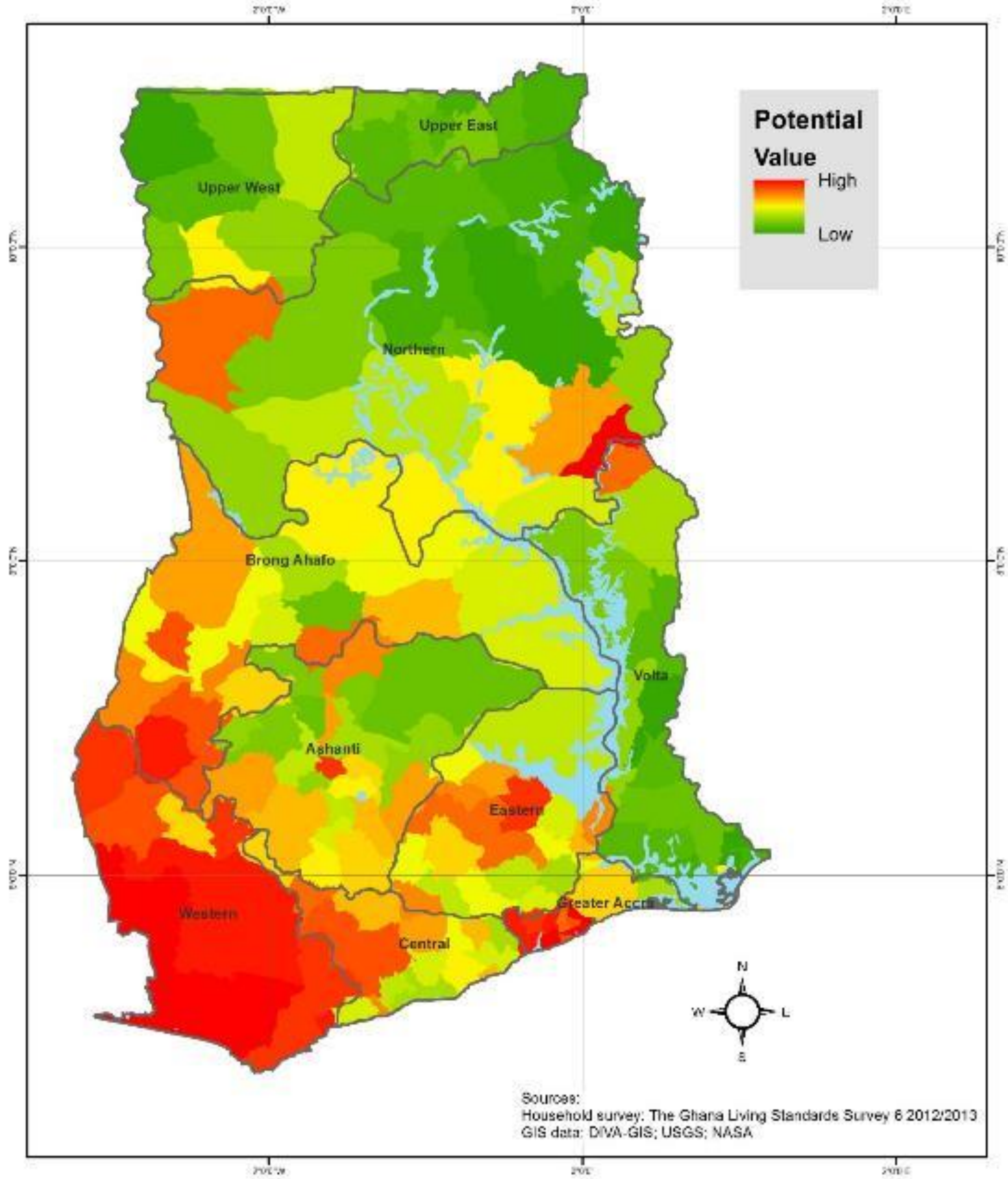

Figure 19: Ghana: Agricultural potential

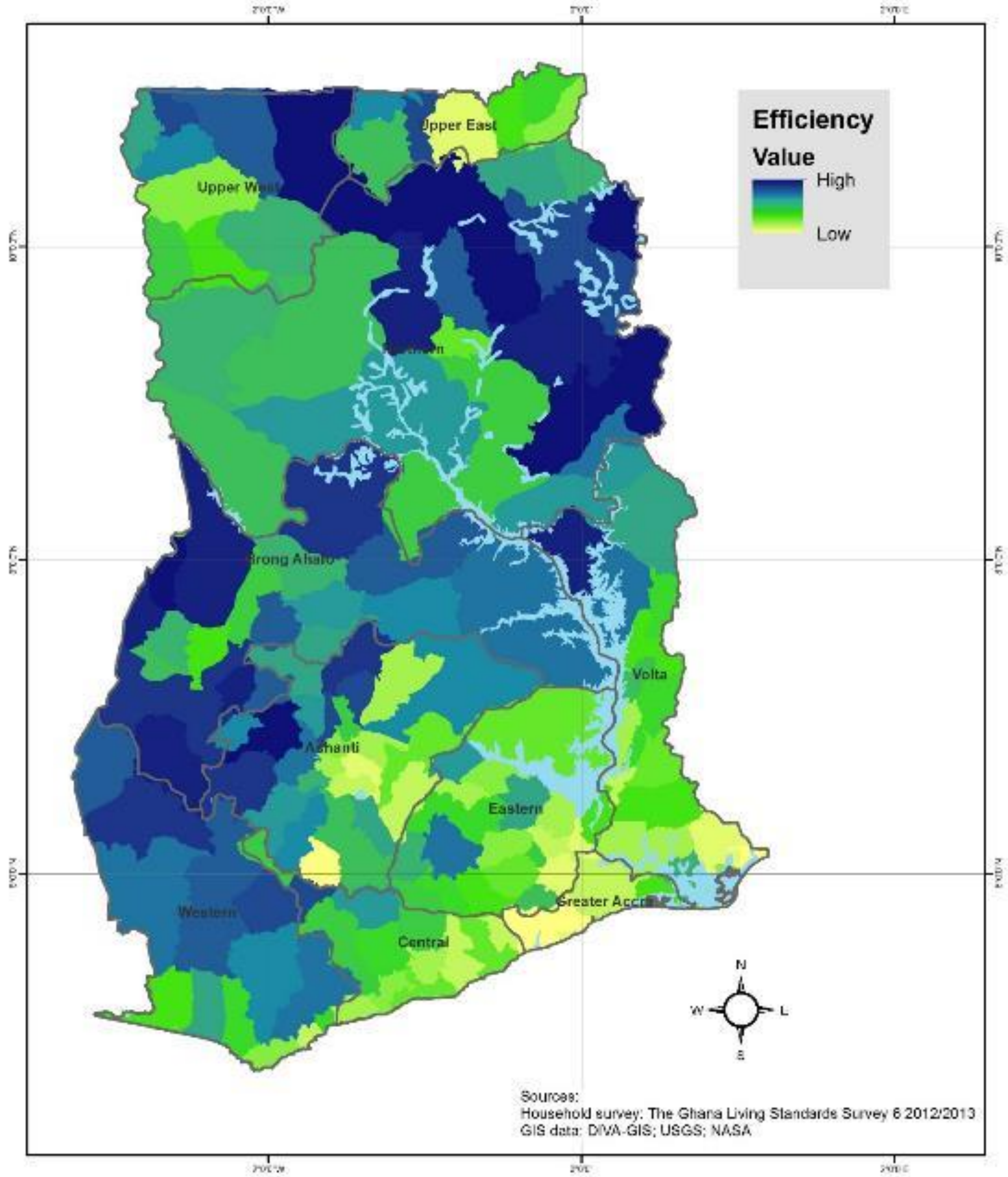

Figure 20: Ghana: Agricultural efficiency

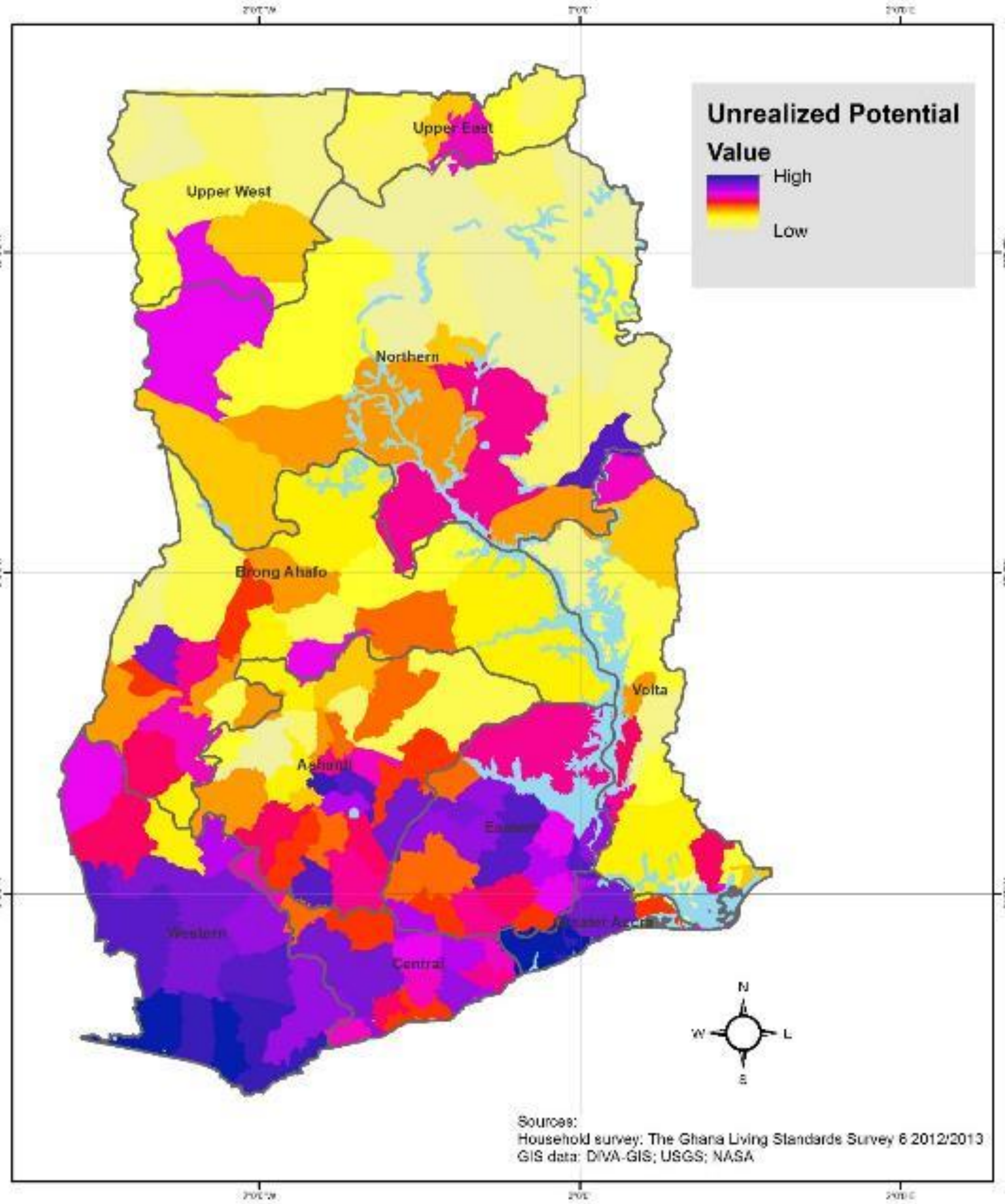

Figure 21: Ghana: Unrealized agricultural potential

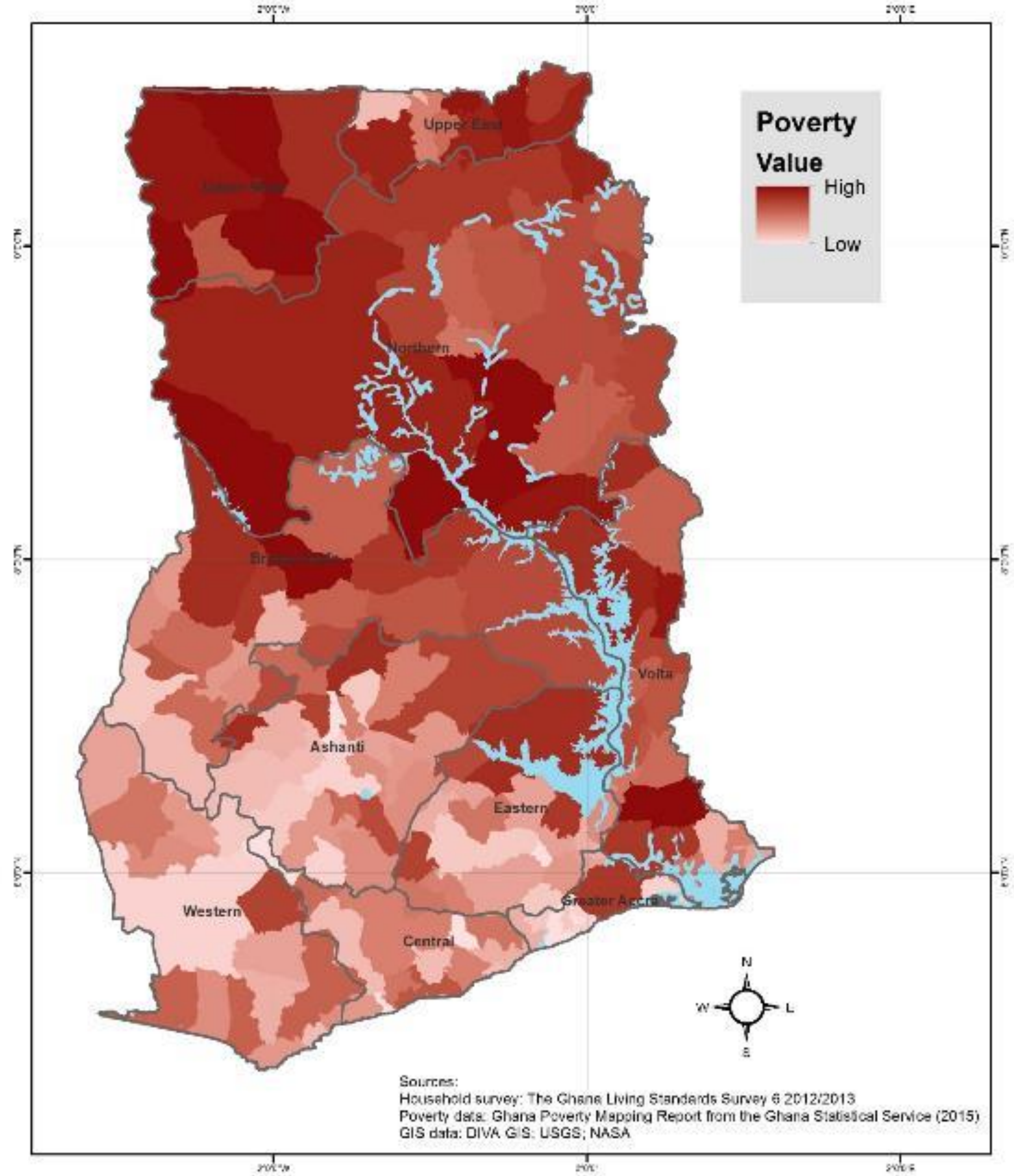

Figure 22: Ghana: Poverty map

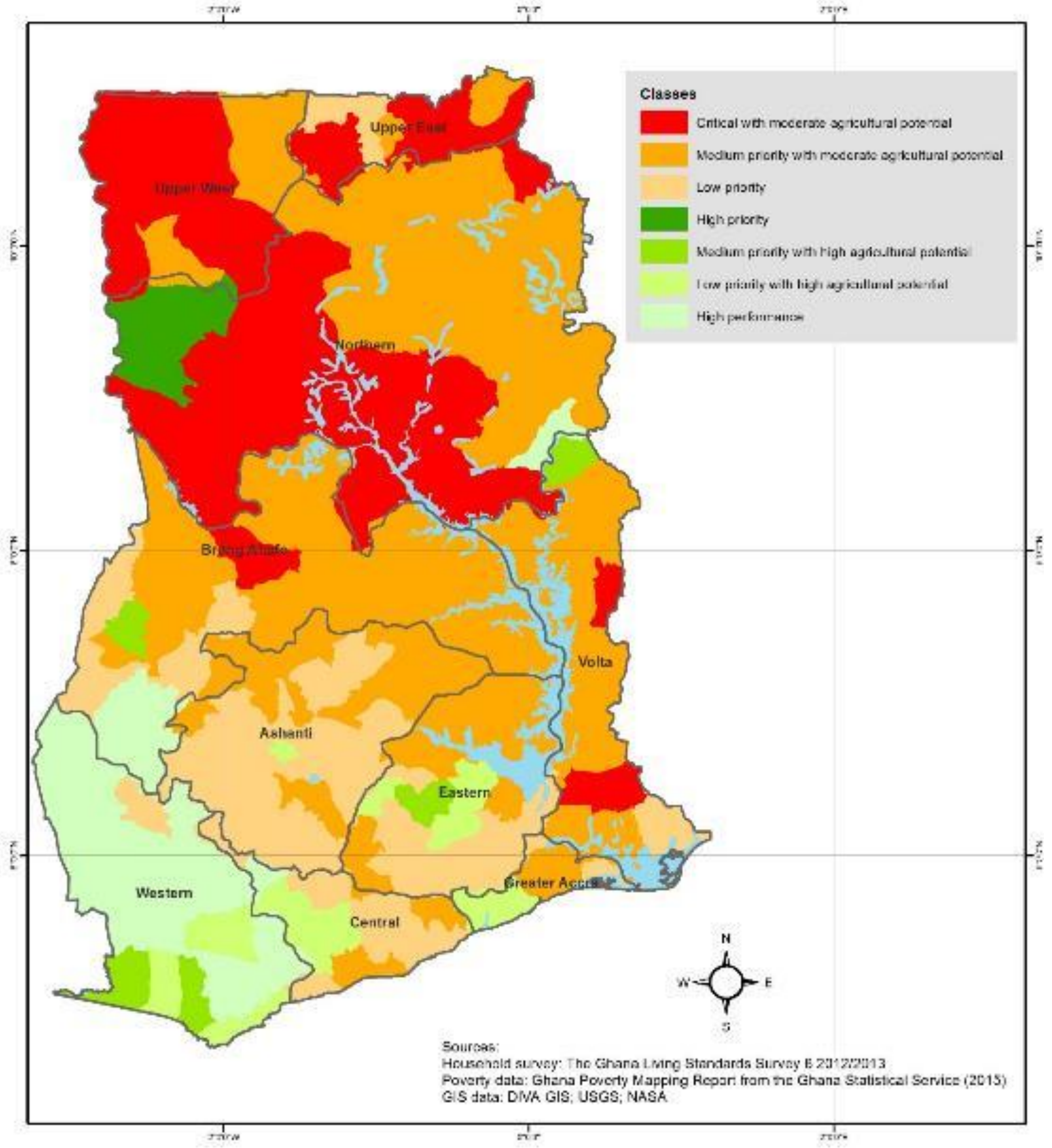

Figure 23: Ghana: Agricultural typology

5.4 Kenya

The data sources used for the estimations and mapping for Kenya are:

- Household survey: The Kenya Integrated Household Budget Survey 2005/2006, available through the National Data Archive of the Kenya National Bureau of Statistics. It has a sample of 13,390 households, out of which 6,049 are used for the frontier estimation, and is representative at the national, provincial, and district levels.
- Poverty data: Basic Report on Well-Being in Kenya from the Kenya National Bureau of Statistics.

Agricultural potential (Figure 24) in Kenya is driven by rainfall patterns, elevation, and local vegetation characteristics. Rainfall is higher in the southern half of the country (see Figure 25), and the combination of high precipitation, better soil quality, higher elevations and cooler temperatures in areas of the (former) Central province and the south of the Rift Valley province allow to produce staple crops and cash crops such as coffee and tea. The maize producing region slightly inland from the coast with the Indian Ocean also has medium to high agricultural potential. Livestock is a stronger driver for the high potential in the grass areas of the north east of Kenya, where rainfall is lower and temperatures are higher. The areas around Lake Victoria are associated with higher population density and more opportunities to diversify incomes for rural households beyond agriculture which explains their low potential levels.

Combining the agricultural potential with the agricultural efficiency estimates (Figure 26) makes it possible to identify where are the areas with the best opportunities for agricultural growth (Figure 27). Due to a combination of higher potential and lower efficiency, the cash cropping regions of the Central and Rift Valley provinces, the maize producing region of the Coast province, and particularly the livestock oriented areas of the North-Eastern province present the largest gaps in terms of potential which can be attained by making investments oriented to increase agricultural efficiency.

Combining the agricultural potential and efficiency estimates with poverty figures (Figure 28) results in the tercile breaks typology shown in Figure 29. The high poverty areas concentrated in the pastoral lands of the North Eastern and Coast regions also have high unrealized agricultural potential (darker blue areas in Figure 27) which make then high priority regions (dark green in Figure 29) for efficiency enhancing innovations in livestock production. Some smaller areas located in the cereal oriented Eastern and Rift Valley regions (maize, millet, sorghum) also show considerable potential gaps and should be targeted for efficiency enhancing innovations. Low potential regions that would benefit from potential enhancing innovations are more dispersed, but are slightly more concentrated in the maize producing southern section of the Coast region and the livestock oriented areas around Lake Turkana in the Rift Valley region.

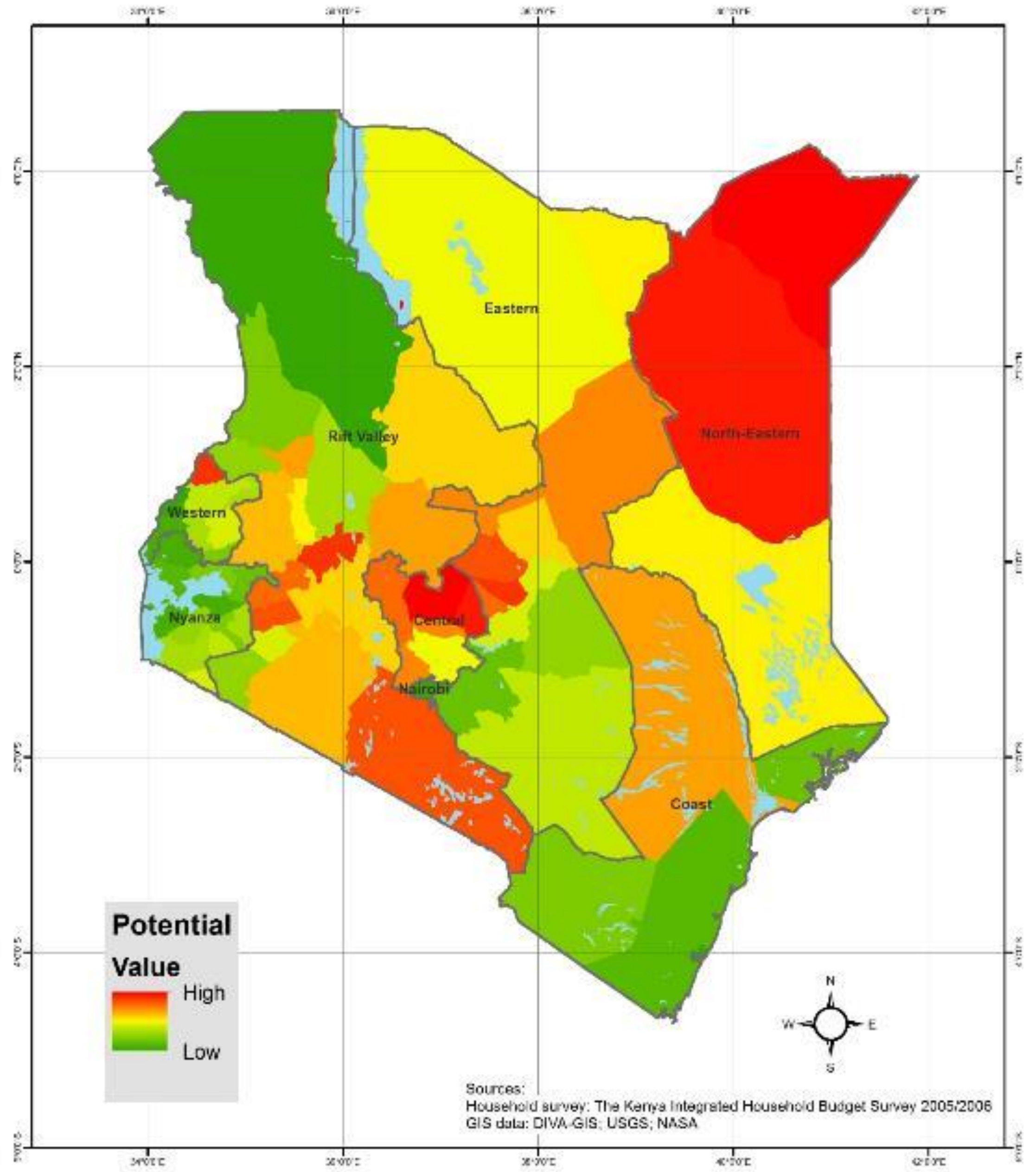

Figure 24: Kenya: Agricultural potential

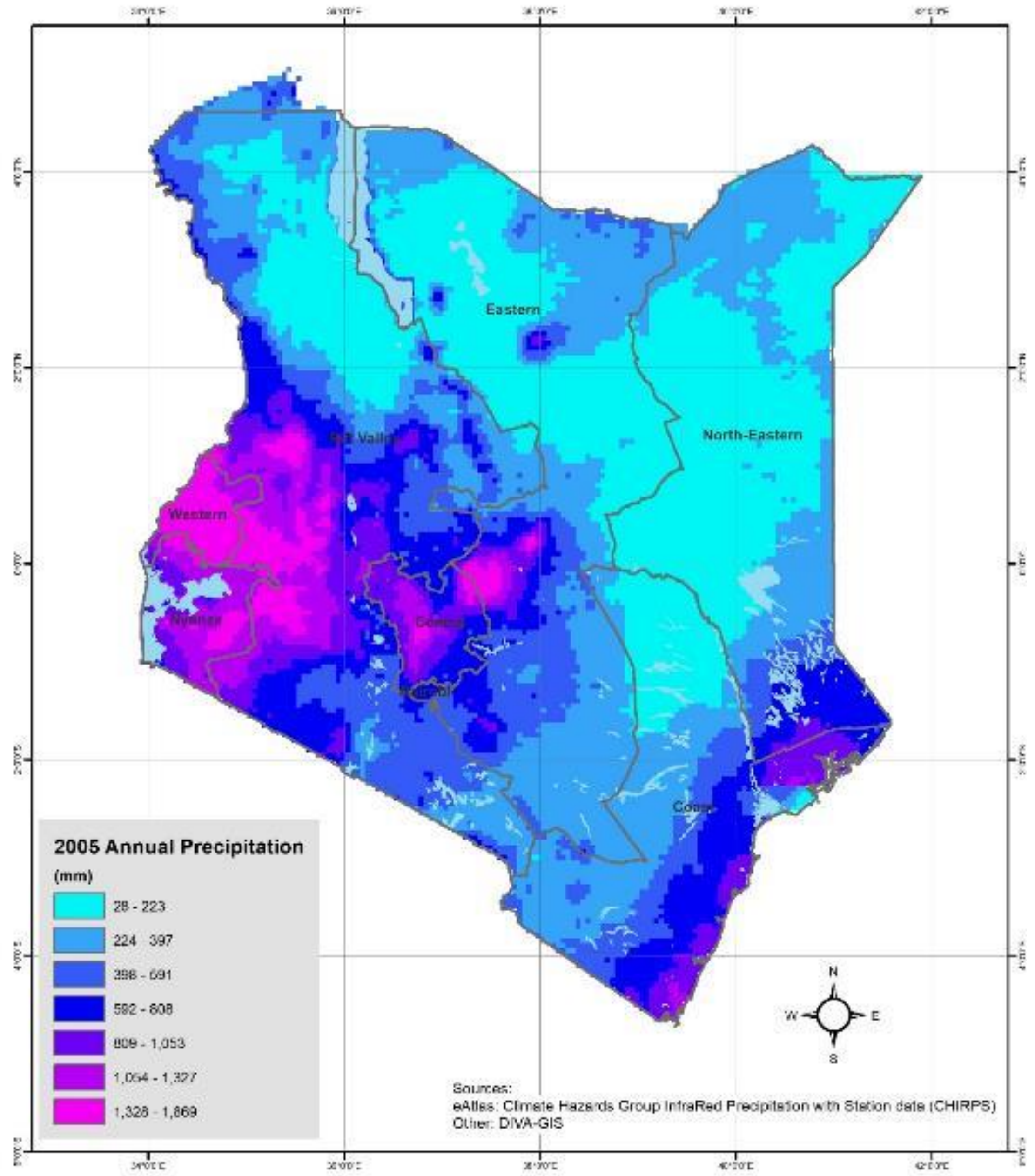

Figure 25: Kenya: Annual precipitation (mm), 2005

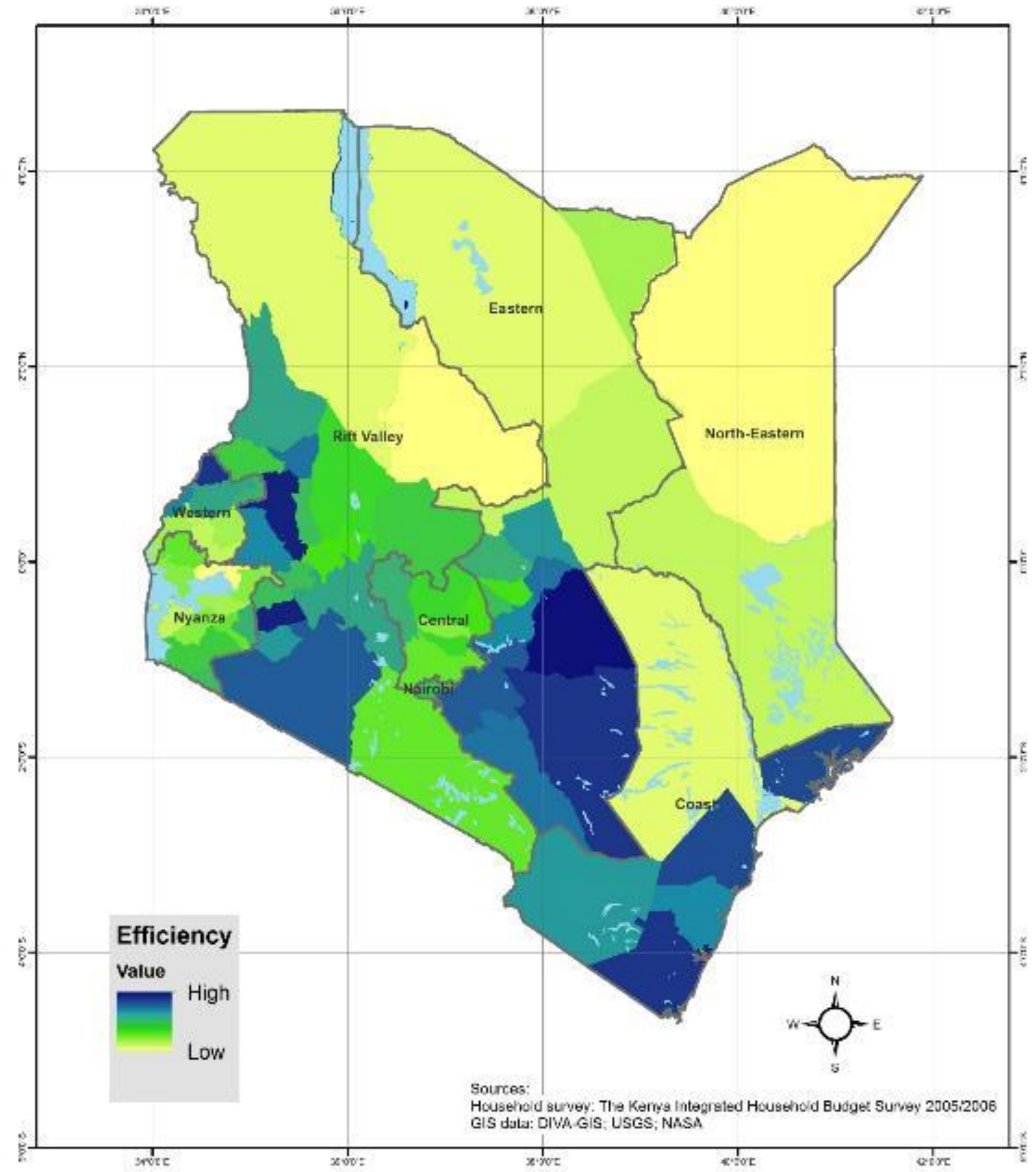

Figure 26: Kenya: Agricultural efficiency

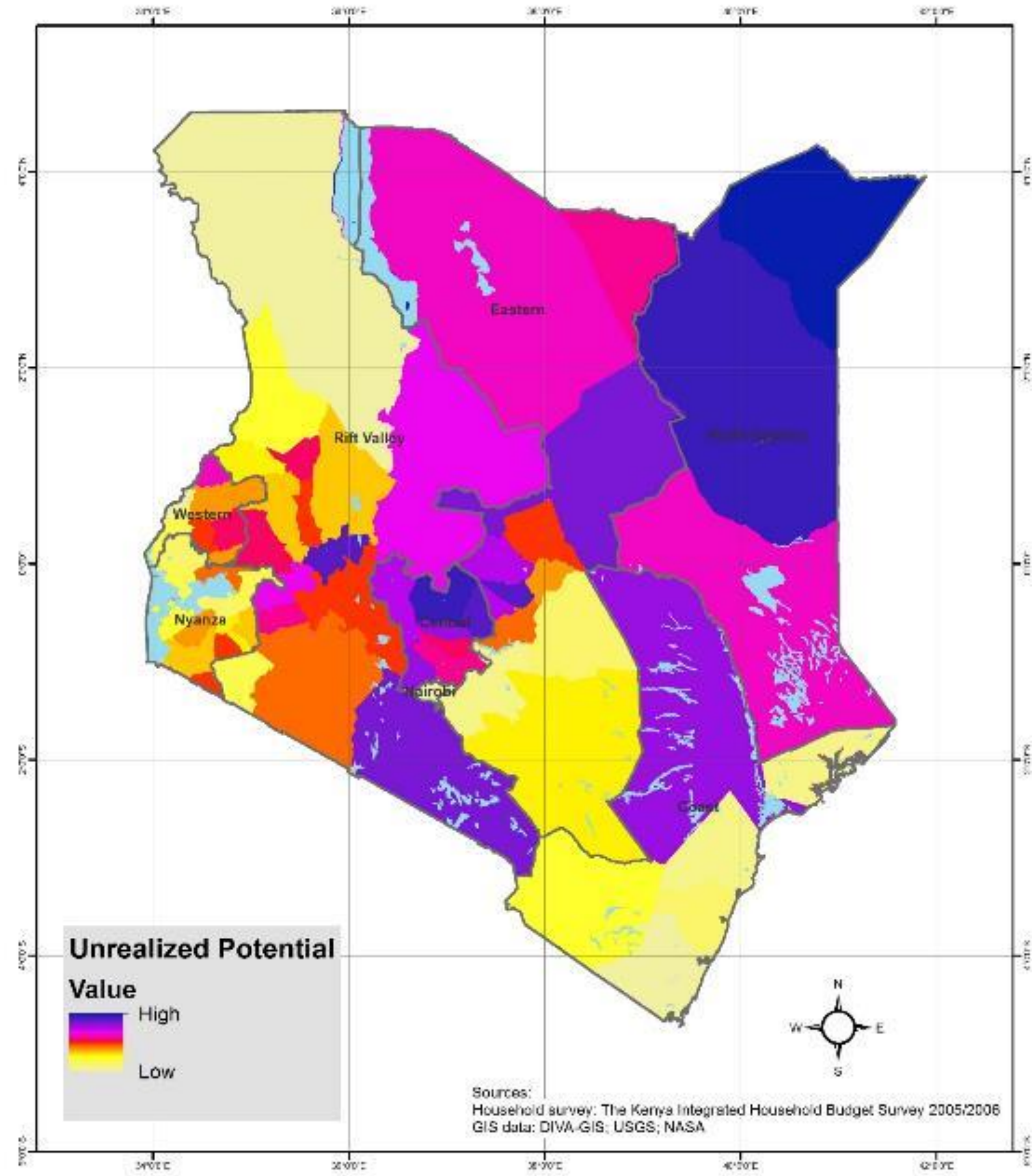

Figure 27: Kenya: Unrealized agricultural potential

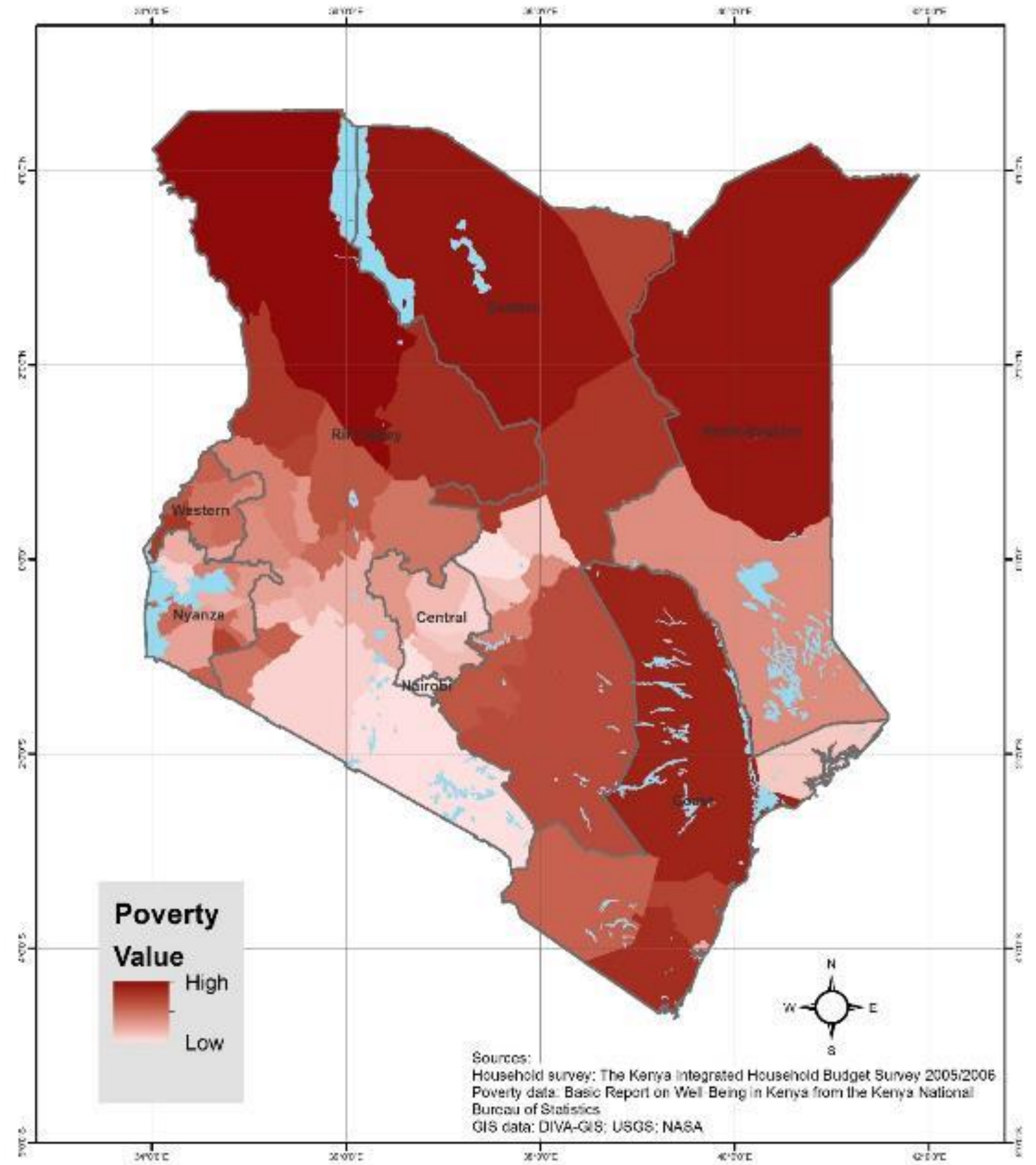

Figure 28: Kenya: Poverty map

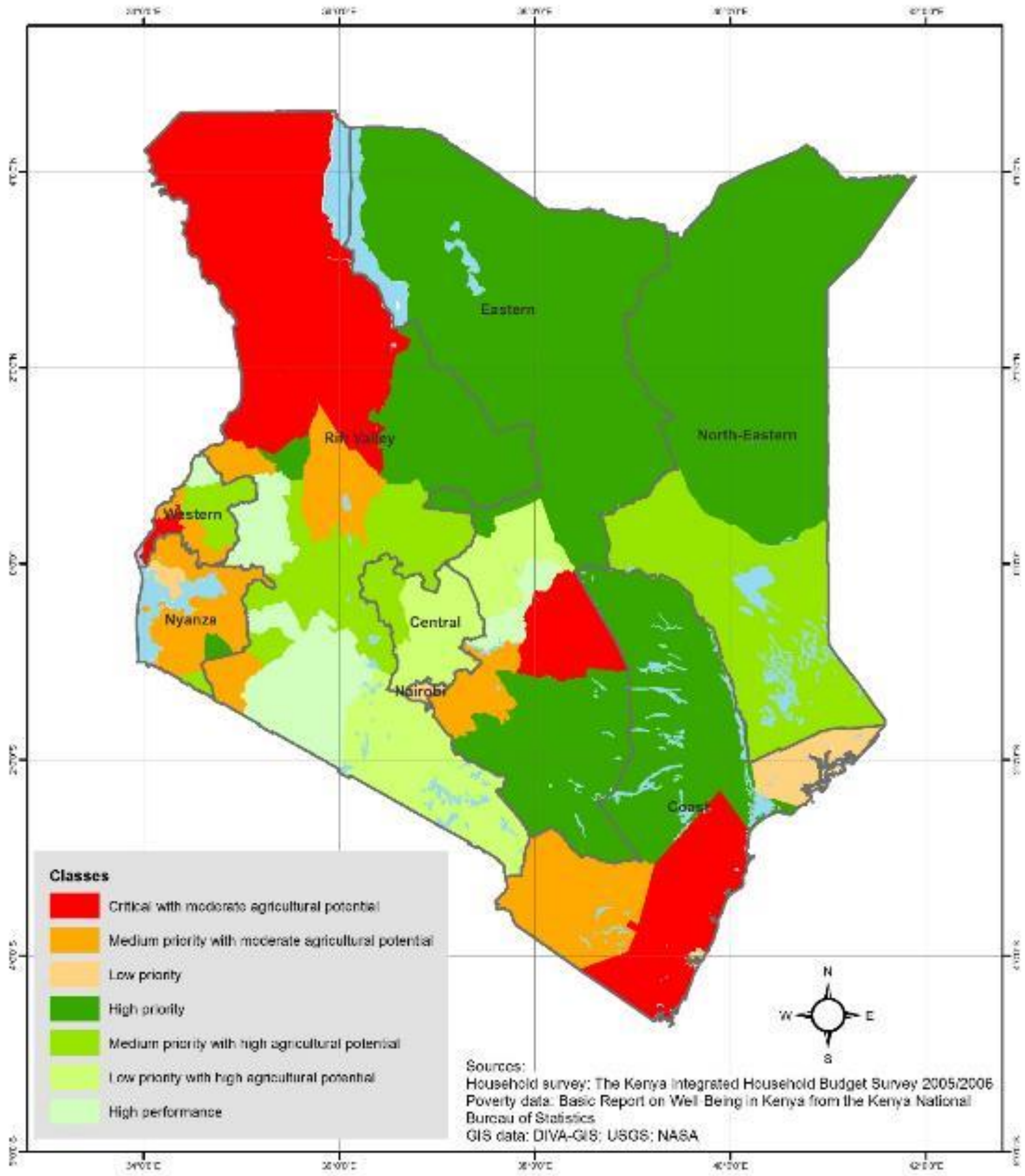

Figure 29: Kenya: Agricultural typology

5.5 Malawi

The data sources used for the estimations and mapping for Malawi are:

- Household survey: The Integrated Household Survey 3 2010/2011, publicly available through the World Bank Microdata Catalog. It has a sample of 12,271 households, out of which 5,822 are used for the frontier estimation, and is representative at the national, regional, district, and urban/rural levels.
- Poverty data: The Integrated Household Survey 3 2010/2011.

The higher precipitation levels and the agroecological suitability for horticulture in the Kasungu Lilongwe Plain (central), and the staple crop producing areas in the north (such as Chipita) explain the high agricultural potential in the northern and central regions of Malawi (Figure 30). This pattern is consistent with the production data available for several crops in the eAtlas, such as maize (Figure 31) and tobacco (Figure 32). The southern region suffers from lower potential due to poorer general weather conditions and lower rainfall levels (Figure 33), which limit the length of the growing periods (less than 120 days in a year). The districts of Chikwawa and Nsanje are an exception to this, and show higher potential than the rest of the southern region due to large scale irrigation projects that create opportunities for growing cash crops in the area.

The spatial distribution of agricultural efficiency (Figure 34) follows a similar pattern than the distribution of agricultural potential, with higher levels in the northern half of the country. The unrealized potential map (Figure 35) shows that despite the high levels of efficiency, potential in the north is high enough for the remaining gap to be significant, and that the levels of efficiency in the southern tip of the country are low enough to offer some opportunities for efficiency enhancing innovations in those areas as well.

Poverty rates in Malawi follow a similar spatial pattern, with higher poverty rates in the south than in the north of the country (Figure 36). Combining the three typology variables, the result is a predominance of low and medium priority areas with high agricultural potential in the north, and critical and high priority areas in the south (Figure 37). Areas in the different shades of green in the typology (darker shades of green indicate higher poverty levels) are areas where efficiency enhancing innovations would be suitable, particularly those in which the levels of unrealized potential are high, including small sections of the districts of Mzimba and Nkhata Bay in the northern region with high potential for coffee and tea production under irrigation. Investments in innovations that enhance agricultural potential or expand the technological frontier should target areas with moderate agricultural potential and medium to high poverty levels (orange and red), which are more predominant in the southern region.

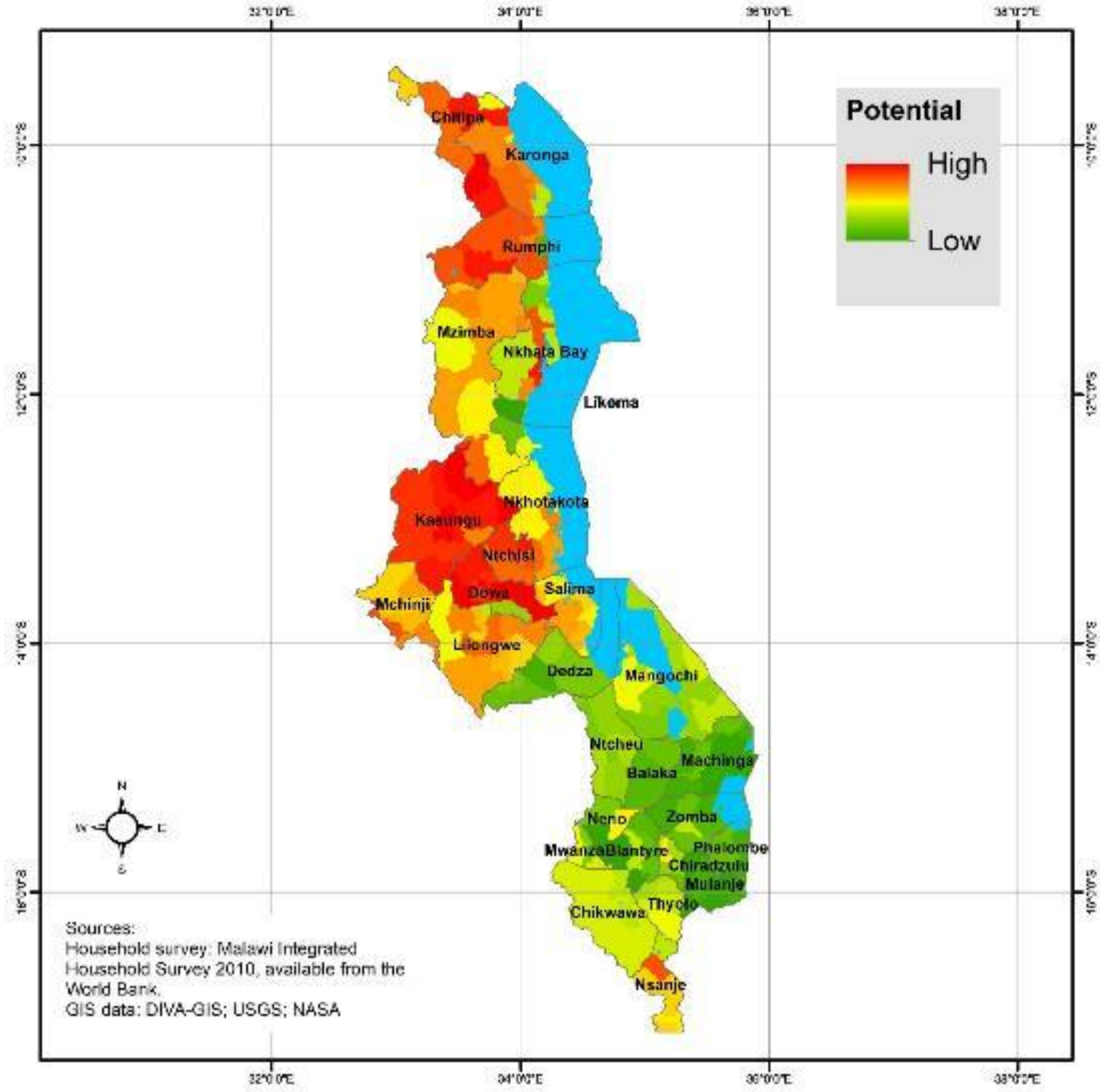

Figure 30: Malawi: Agricultural potential

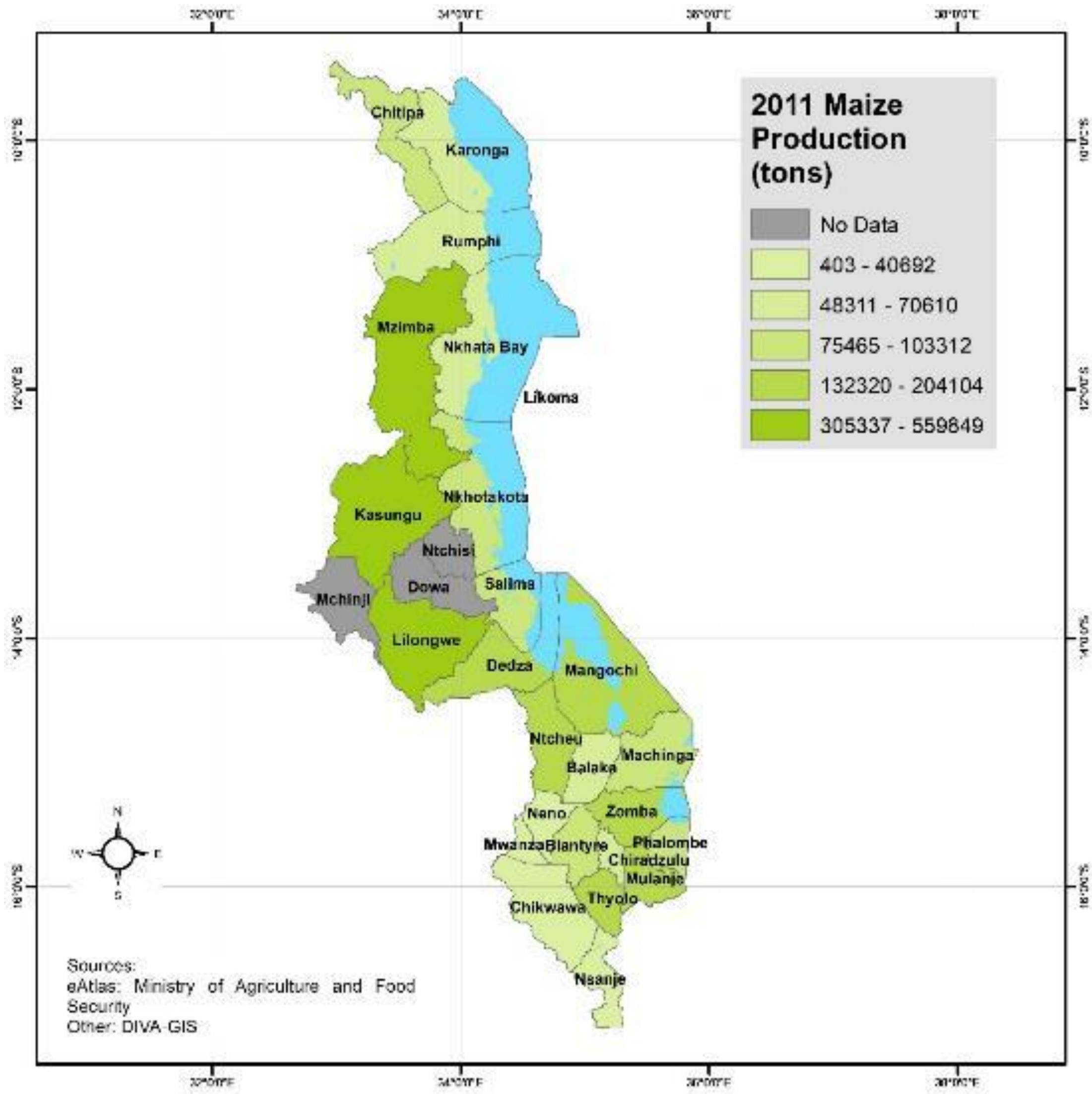

Figure 31: Malawi: Maize production (tons), 2011

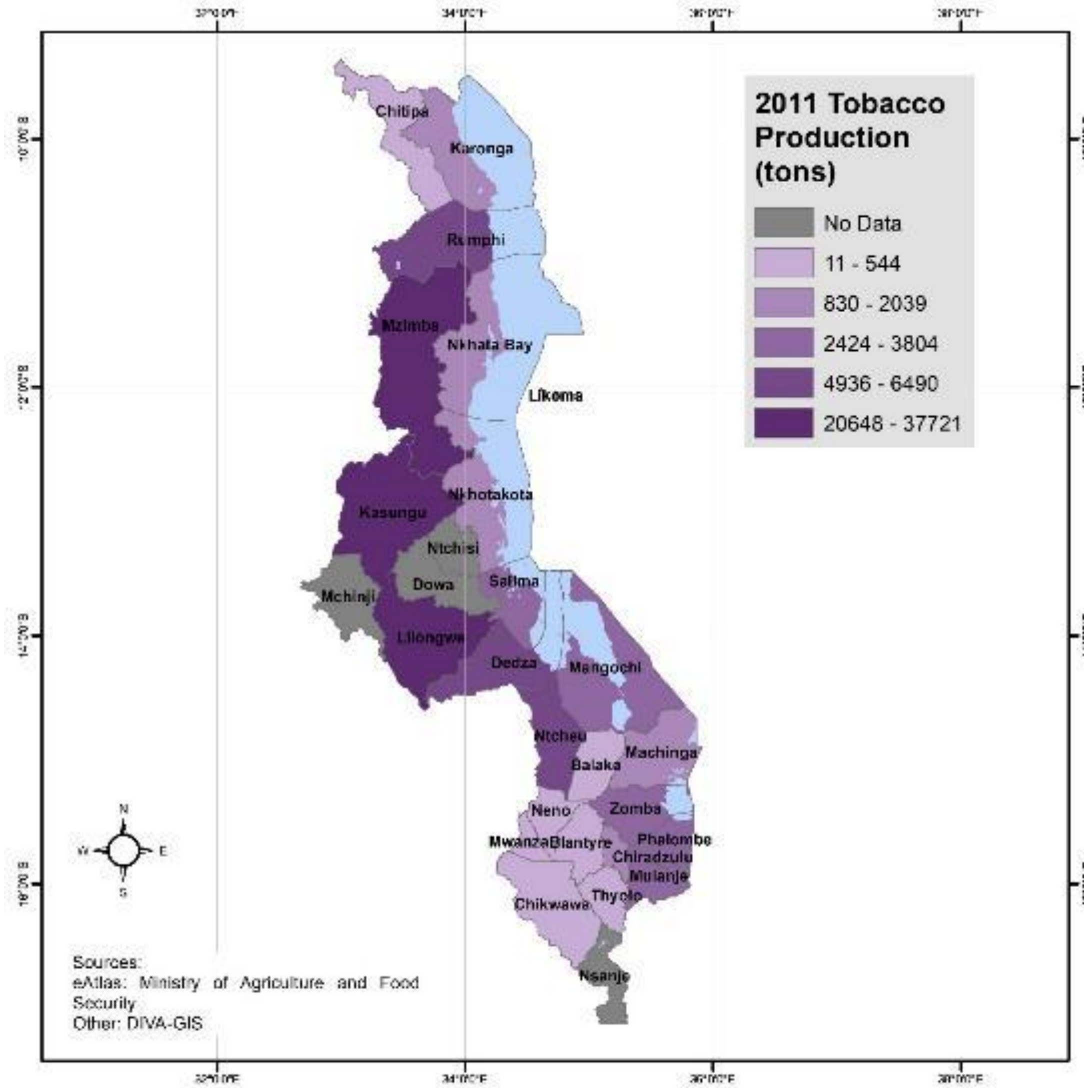

Figure 32: Malawi: Tobacco production (tons), 2011

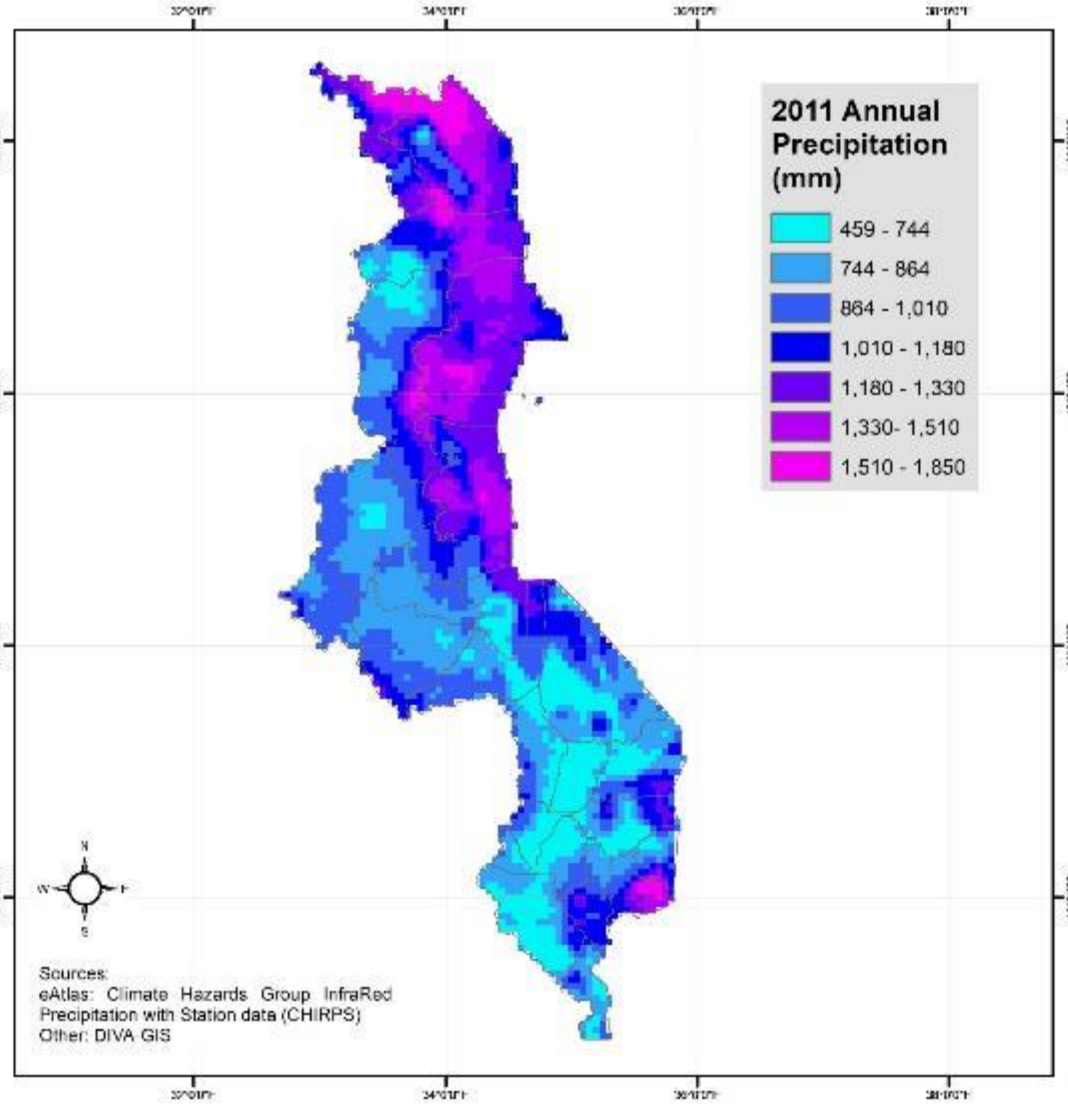

Figure 33: Malawi: Annual precipitation (mm), 2011

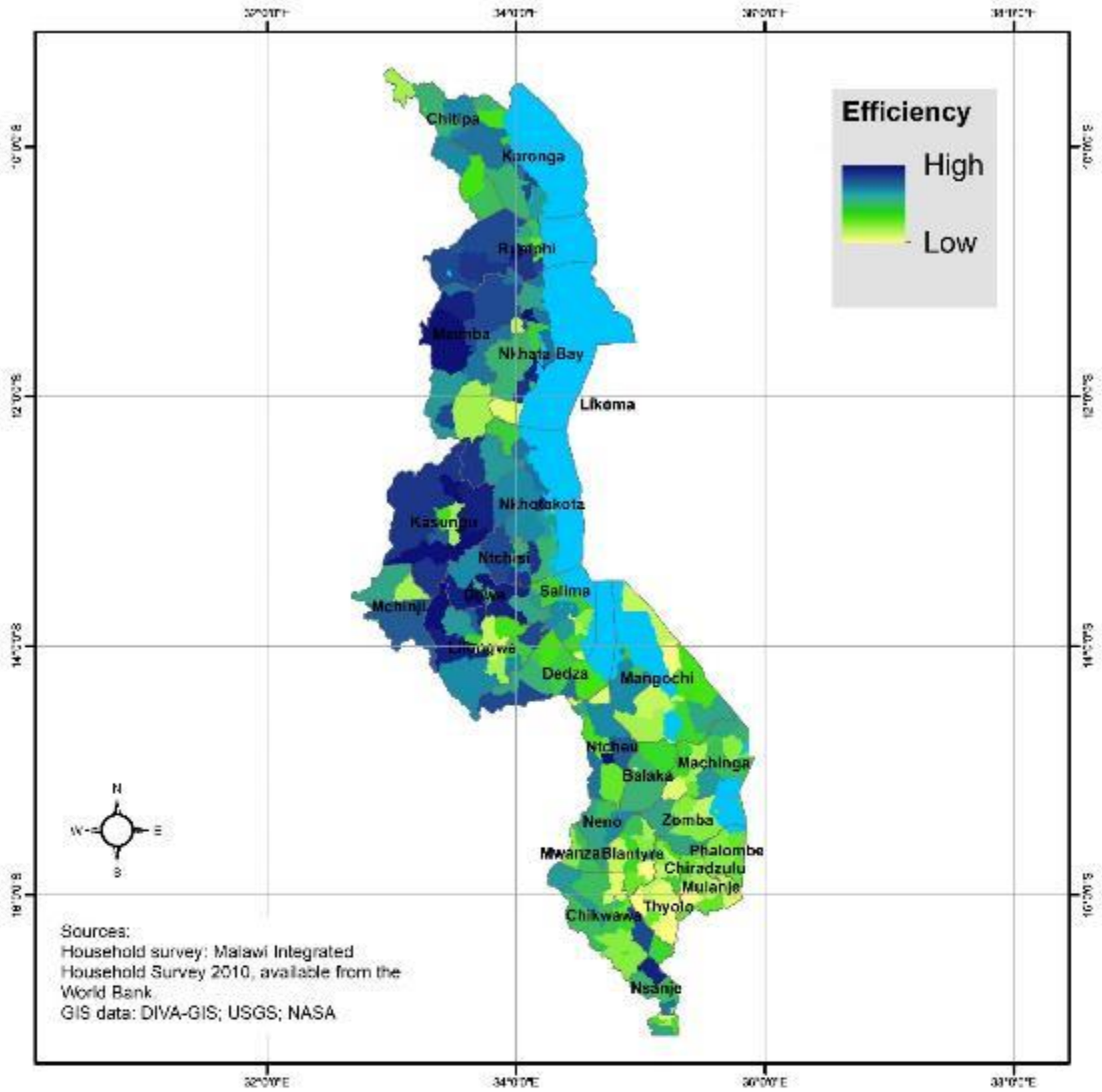

Figure 34: Malawi: Agricultural efficiency

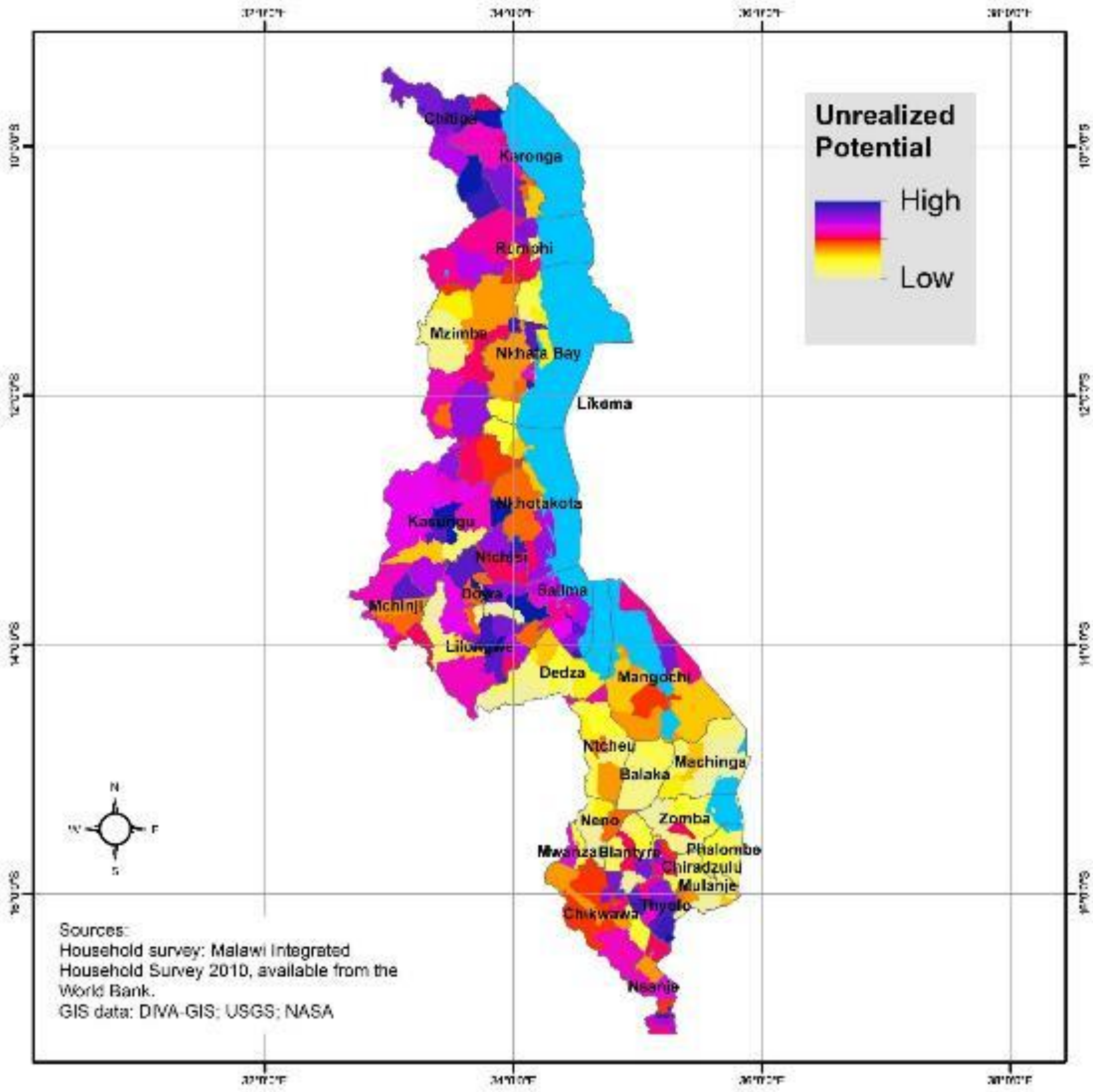

Figure 35: Malawi: Unrealized agricultural potential

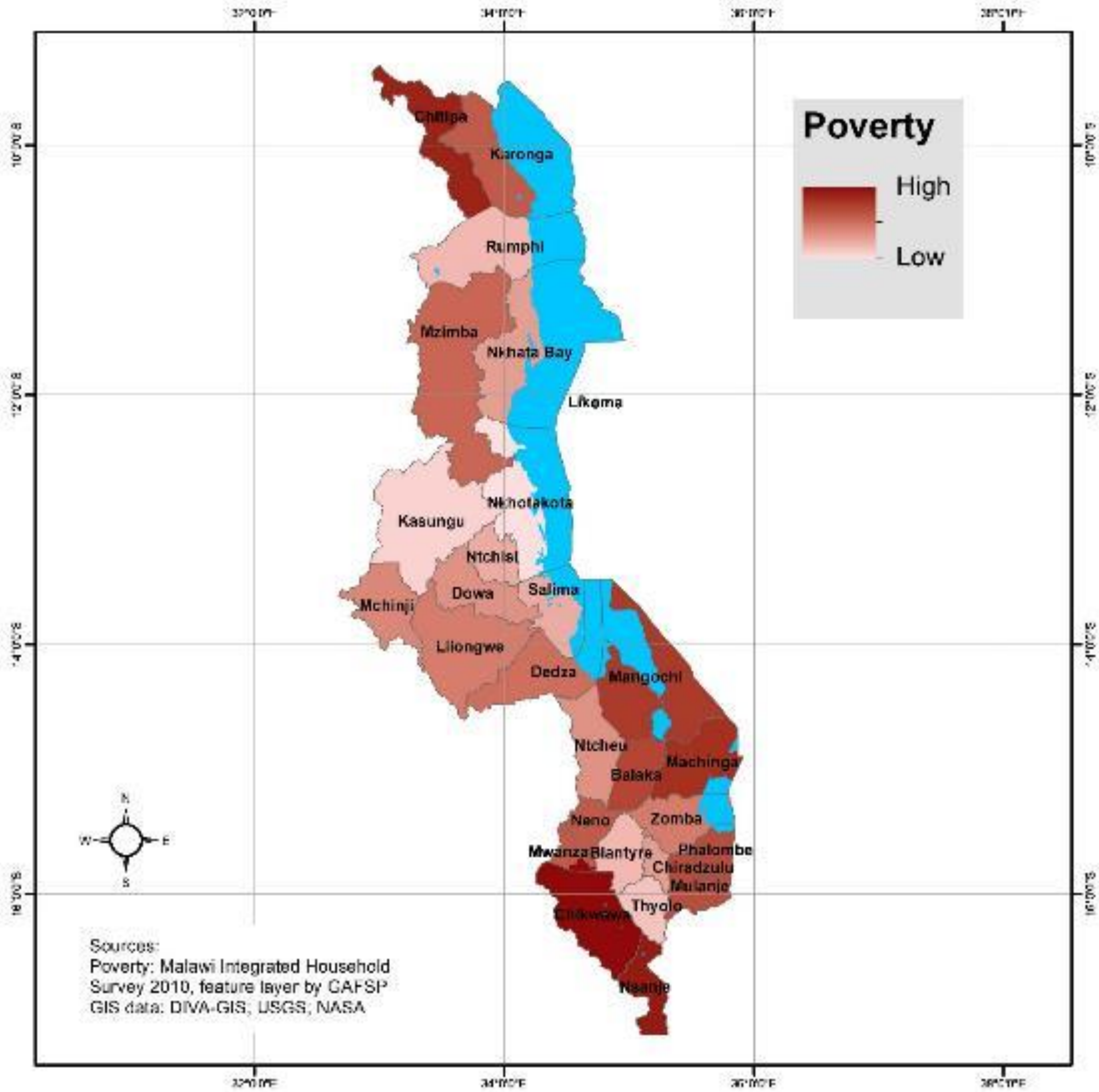

Figure 36: Malawi: Poverty map

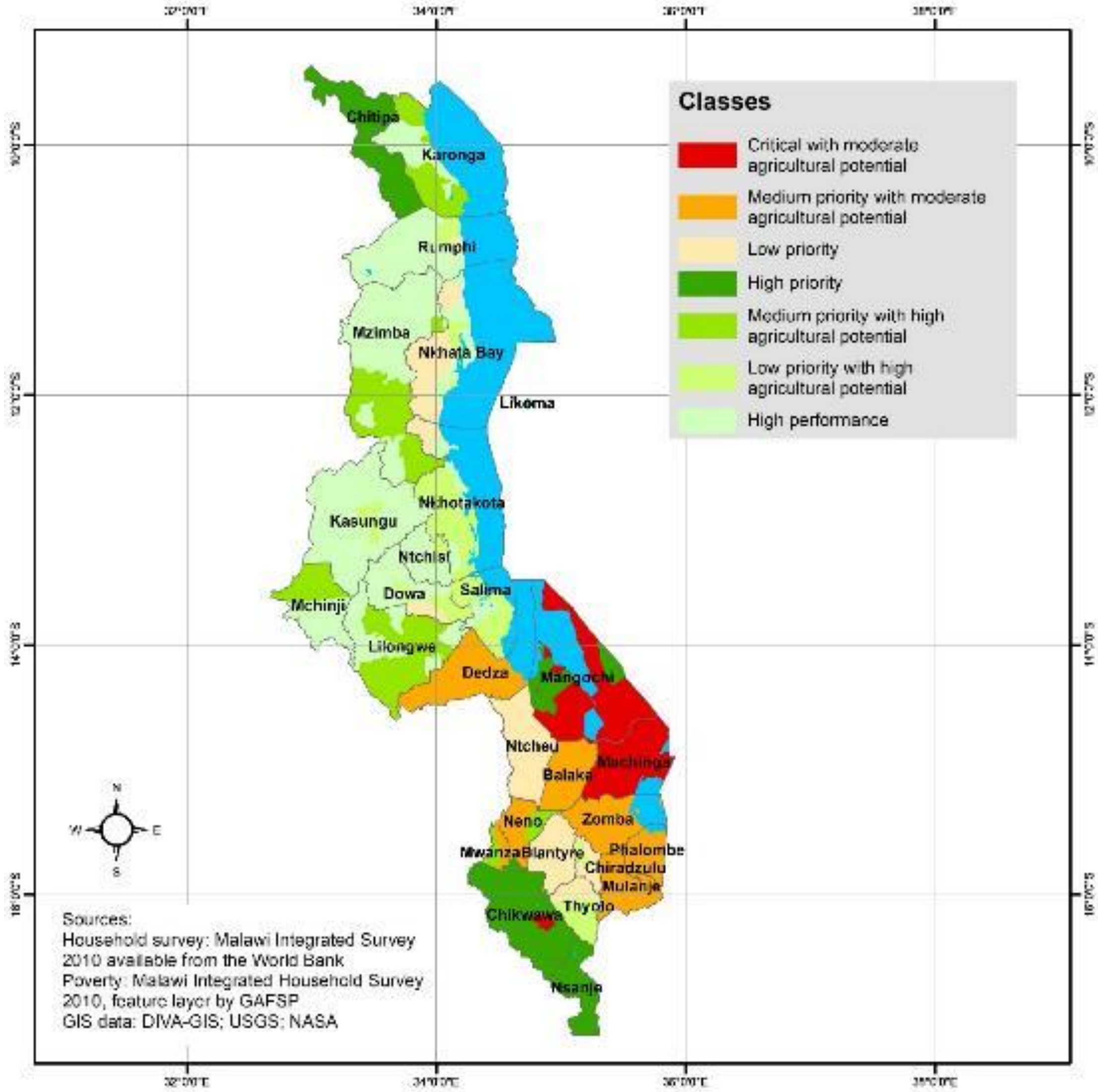

Figure 37: Malawi: Agricultural typology

5.6 Nigeria

The data sources used for the estimations and mapping for Nigeria are:

- Household survey: The General Household Survey Wave 3 2015/2016, publicly available through the World Bank Microdata Catalog. It has a sample of 4,581 households, out of which 2,162 are used for the frontier estimation, and is representative at the national, zonal, and urban/rural levels.
- Poverty data: Nigeria Poverty Profile 2010 from the National Bureau of Statistics.

The agricultural potential map for Nigeria (Figure 38) shows a high concentration of areas with potential for agricultural activities in the south-western zone, as well as some in the northern central zone. The high potential in the south-western zone comes from the income generating opportunities associated with cash crop farming including cocoa and palm oil, and coastal fishing activities from Lagos to Port Harcourt. In the northern central zone, areas in the central highland and plain regions around Abuja show high potential due to the vast web of rivers and water sources and a relatively dense zone for irrigation development that can be further exploited given this area's ideal location close to large urban markets. The general spatial pattern show in the agricultural potential map is supported by the annual precipitation pattern shown in Figure 39.

The agricultural efficiency map and the unrealized potential map are shown in Figure 40 and Figure 41. The combination of high efficiency levels and low potential in the North-East zone (particularly the states of Bauchi, Gombe, and Taraba) result in low levels of potential left to be gained without investing in frontier shifting innovations. Alternatively, high efficiency areas in the south-western and Northern central zones still have significant unrealized potential gaps due to the underlying high potential levels. The northern border area limiting with Niger also displays high levels of unrealized potential due to a combination of medium levels of potential and low to medium levels of efficiency.

The poverty map (Figure 42) generally follows a similar spatial pattern as the agricultural potential map, with high potential areas showing lower levels of poverty. Figure 43 shows the agricultural typology map resulting from combining potential, efficiency, and poverty. In general, better performing areas are in the south-western zone of the country, and higher priority and critical regions become more common moving towards the northeast. This reflects the higher agricultural potential and lower poverty rates of the south-western zone, as well as the relatively less friendly agricultural environment in the Sahelian region towards the north and northeast. However, potential enhancing innovations should be considered in this area due to the local predominance of staple crops such as maize, yam, potatoes, sorghum, millet, cowpeas, etc. which are key for food security of rural households.

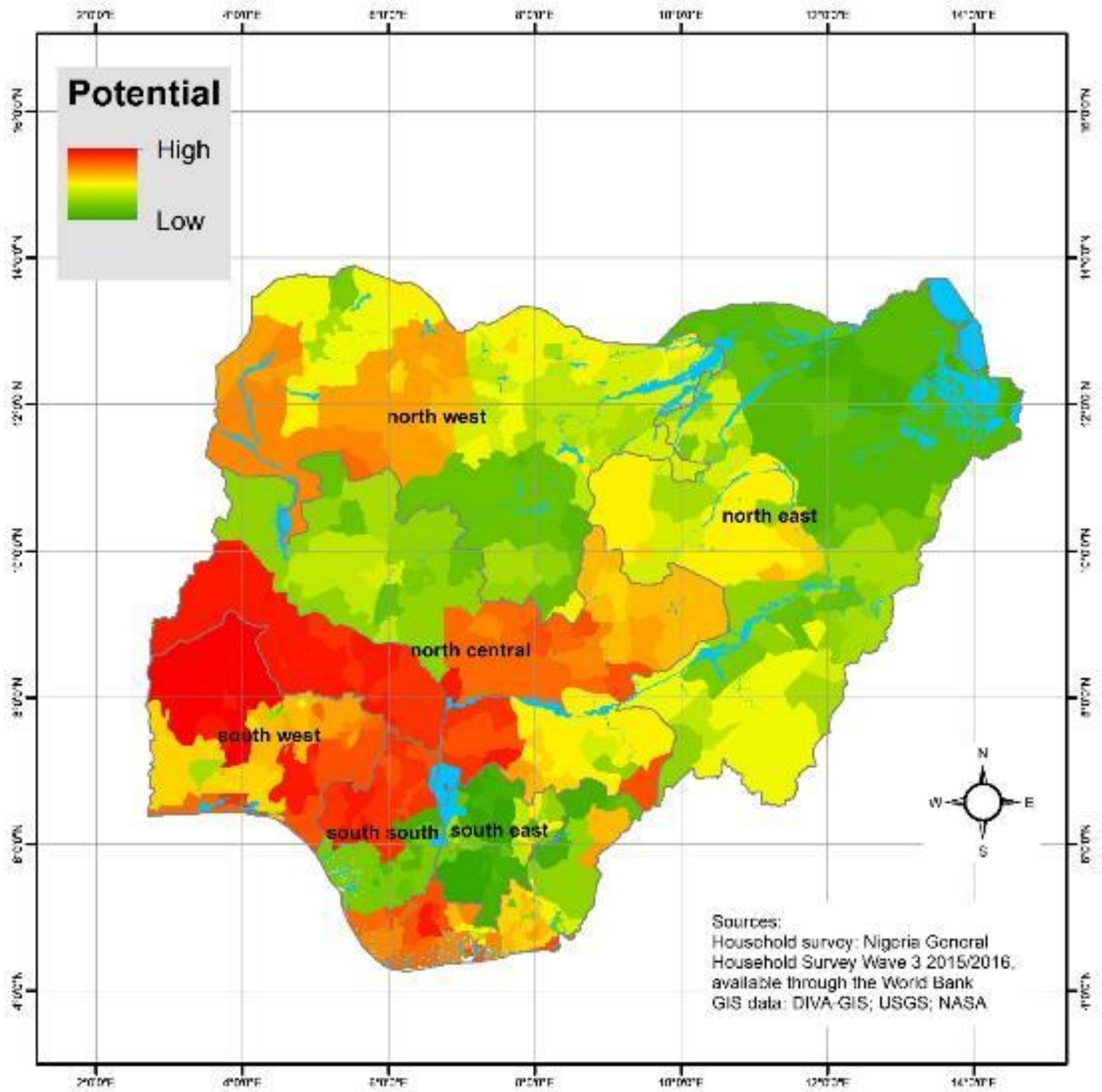

Figure 38: Nigeria: Agricultural potential

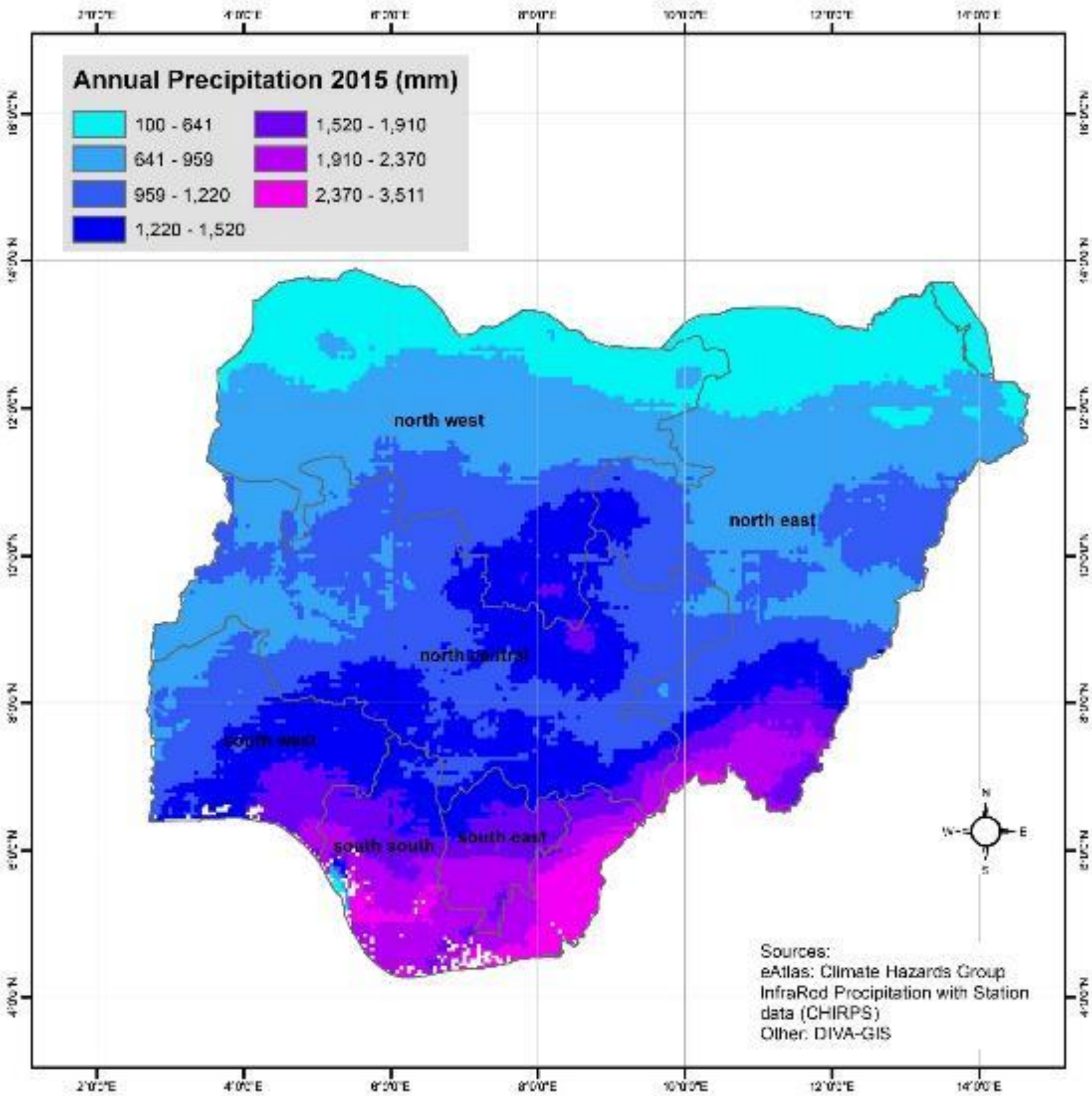

Figure 39: Nigeria: Annual precipitation (mm), 2015

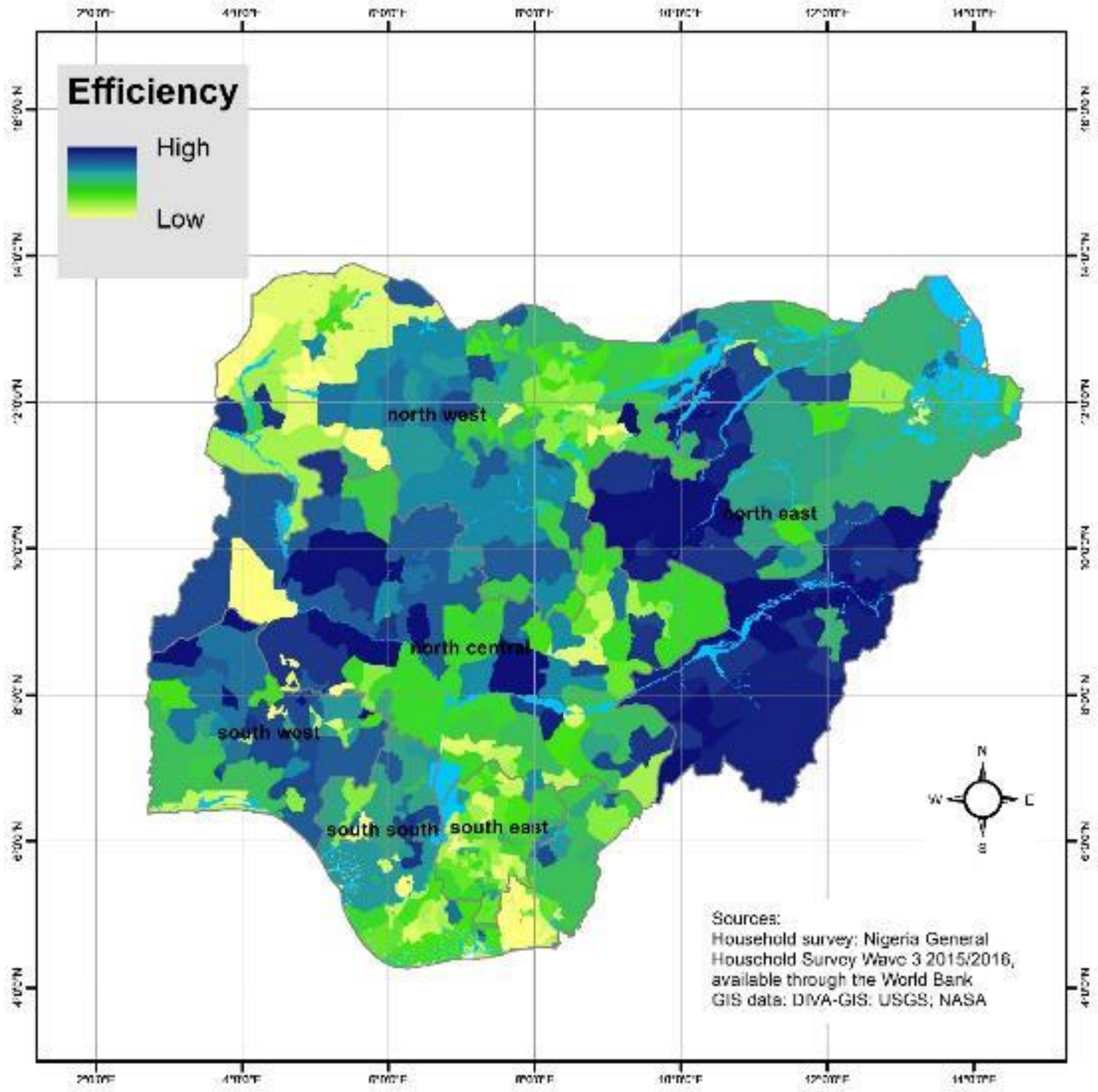

Figure 40: Nigeria: Agricultural efficiency

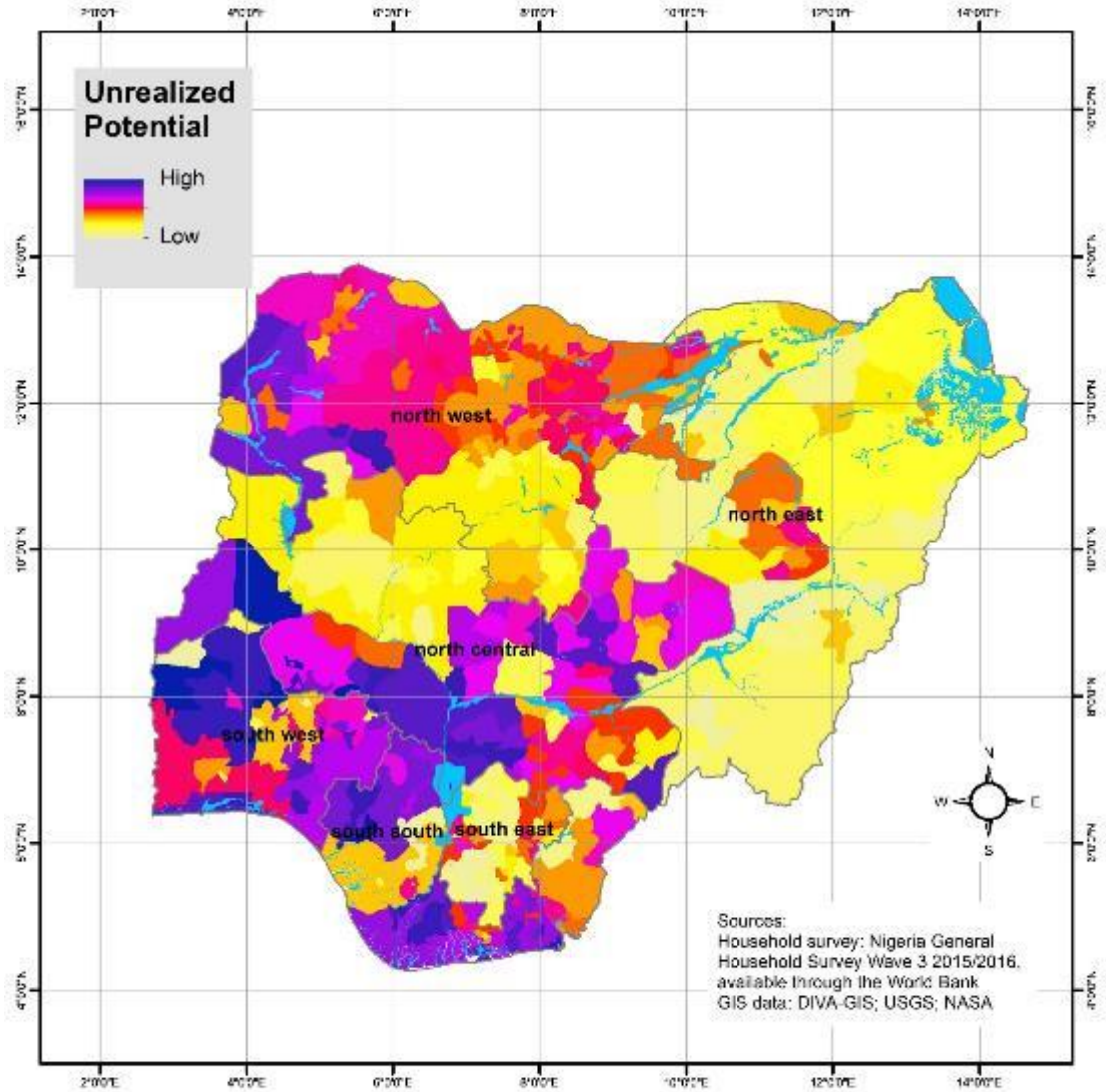

Figure 41: Nigeria: Unrealized agricultural potential

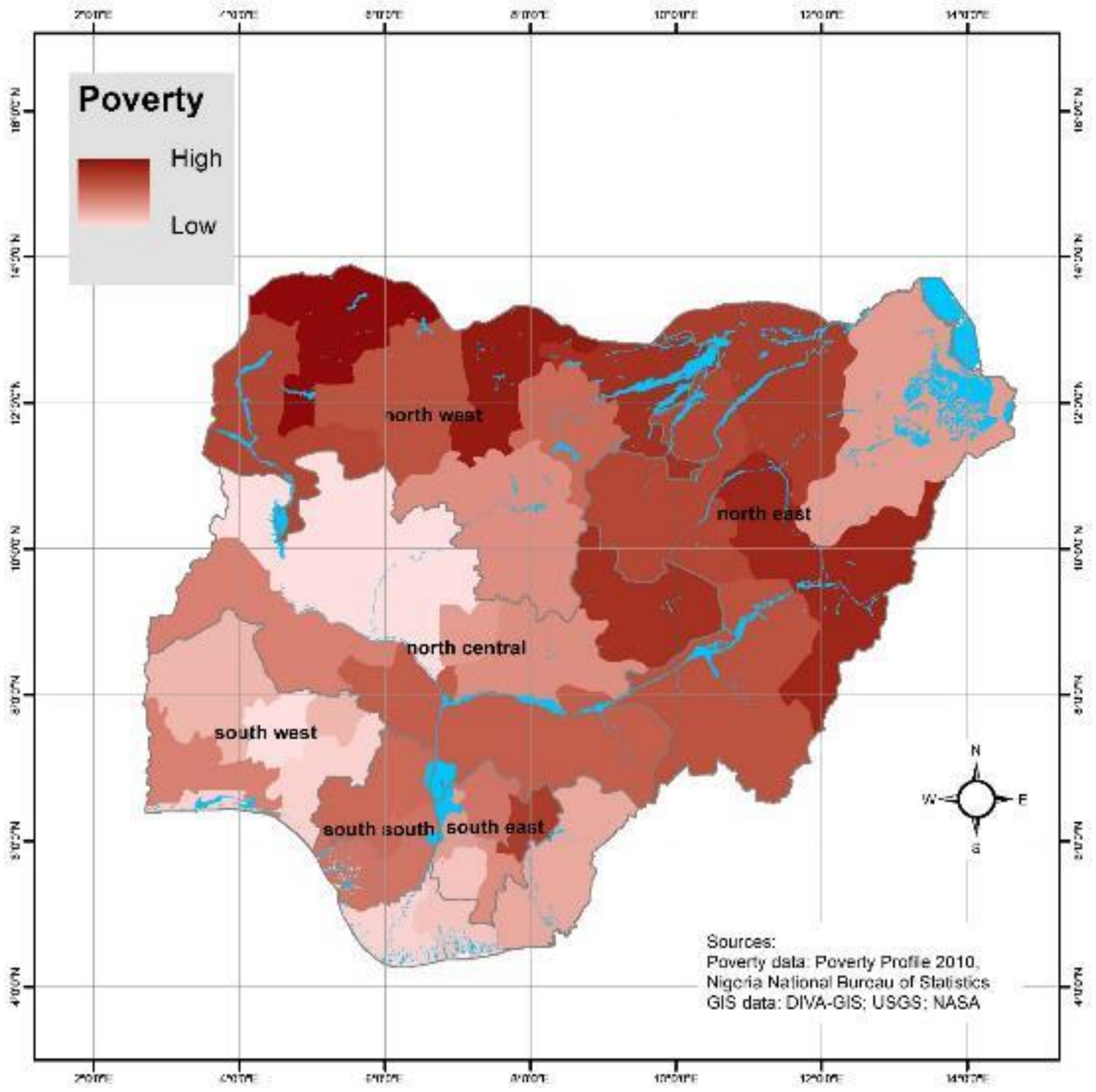

Figure 42: Nigeria: Poverty map

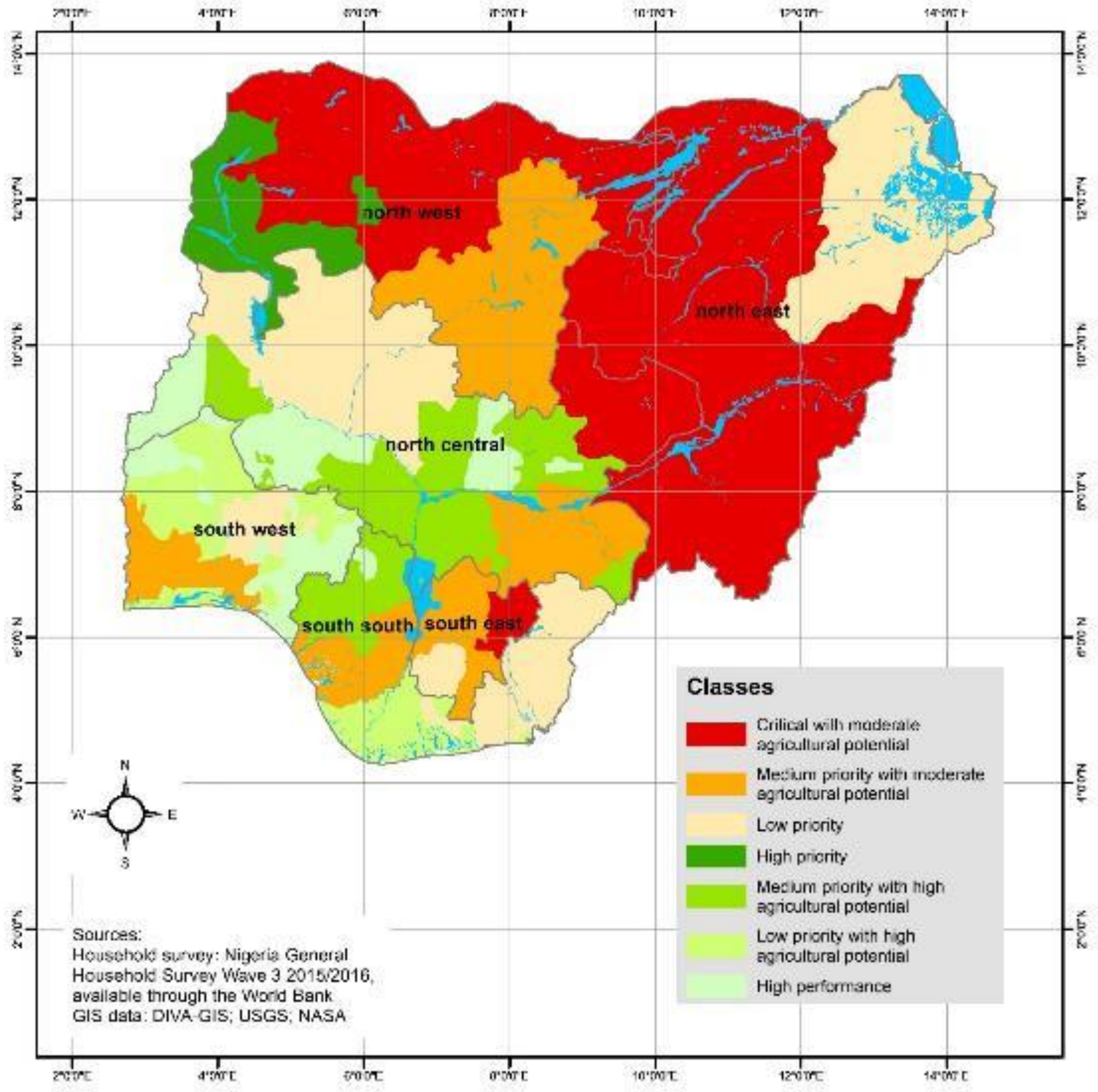

Figure 43: Nigeria: Agricultural typology

5.7 Togo

The data sources used for the estimations and mapping for Togo are:

- Household survey: *Questionnaire des Indicateurs de Base de Bien-Être* 2011, publicly available through the World Bank Microdata Catalog. It has a sample of 6,048 households, out of which 2,739 are used for the frontier estimation, and is representative at the national and subgroup level (Grand Lom Lomé, other towns, rural south and rural north).
- Poverty data: http://www.arcgis.com/home/item.html?id=d4b4fe7952014d61879007c83ac374e4

Despite being one of the smallest countries of West Africa, Togo's territory covers several bioclimatic regions and this heterogeneity is reflected in the agricultural potential map (Figure 44). Northern Togo is characterized by the seasonal Sudanian climate, with a single rainy season, which is reflected in the annual precipitation map from the eAtlas (Figure 45). Agriculture is gaining ground to the woodlands and savannas that are predominant in the north, but this region's exposure to dry Harmattan winds and proneness to drought (as seen by the red areas in Figure 46) results in low agricultural potential. The wooded landscapes and isolated dense tropical forest remnants in the Togo (Atacora) mountain range crossing the Centre region also results in low potential for agriculture. The southern half of the country falls into the Guinean climatic region, characterized by two rainy seasons and higher agricultural potential. The coastal area, however, is part of the Dahomey Gap, a relatively dry savanna zone receiving an average of only 900 mm of rainfall per year and reduced agricultural potential.

Combining agricultural potential (Figure 44) with agricultural efficiency (Figure 47) results in the unrealized potential map (Figure 48). Low potential and high efficiency levels in the north (Savanes) result in little agricultural potential left to be exploited without investing in frontier shifting innovations. The highest unrealized potential levels are found under the favorable rain and agroecological conditions of the Guinean climate in the Plateaux region, especially around the "cocoa-coffee triangle" formed by Kpalimé , Badou and Atakpamé with naturally rich soils and humid and warm climate. Figure 49 shows that poverty follows the spatial pattern of the agricultural potential map, with high potential areas being associated with lower poverty rates, with the exception of the Maritime region where the proximity to Lomé and other major urban centers reduces the importance of the role of agriculture as the major source of income.

The agricultural typology map is shown in Figure 50. The high poverty areas in the Savanes region (north) and the Centre region fall in different classes due to the differences in their agricultural potential classification, with the north falling in the critical (red) class due to its moderate potential, and the Centre region falling in the high priority class due to its medium potential classification. The high potential Plateaux region combines high, medium and low priority areas (shades of green) which result from how the tercile breaks approach classifies poverty levels in this region. High performance regions appear in the Plateaux region consistent with the high productivity and income generating capacity of areas like the cocoa-coffee triangle.

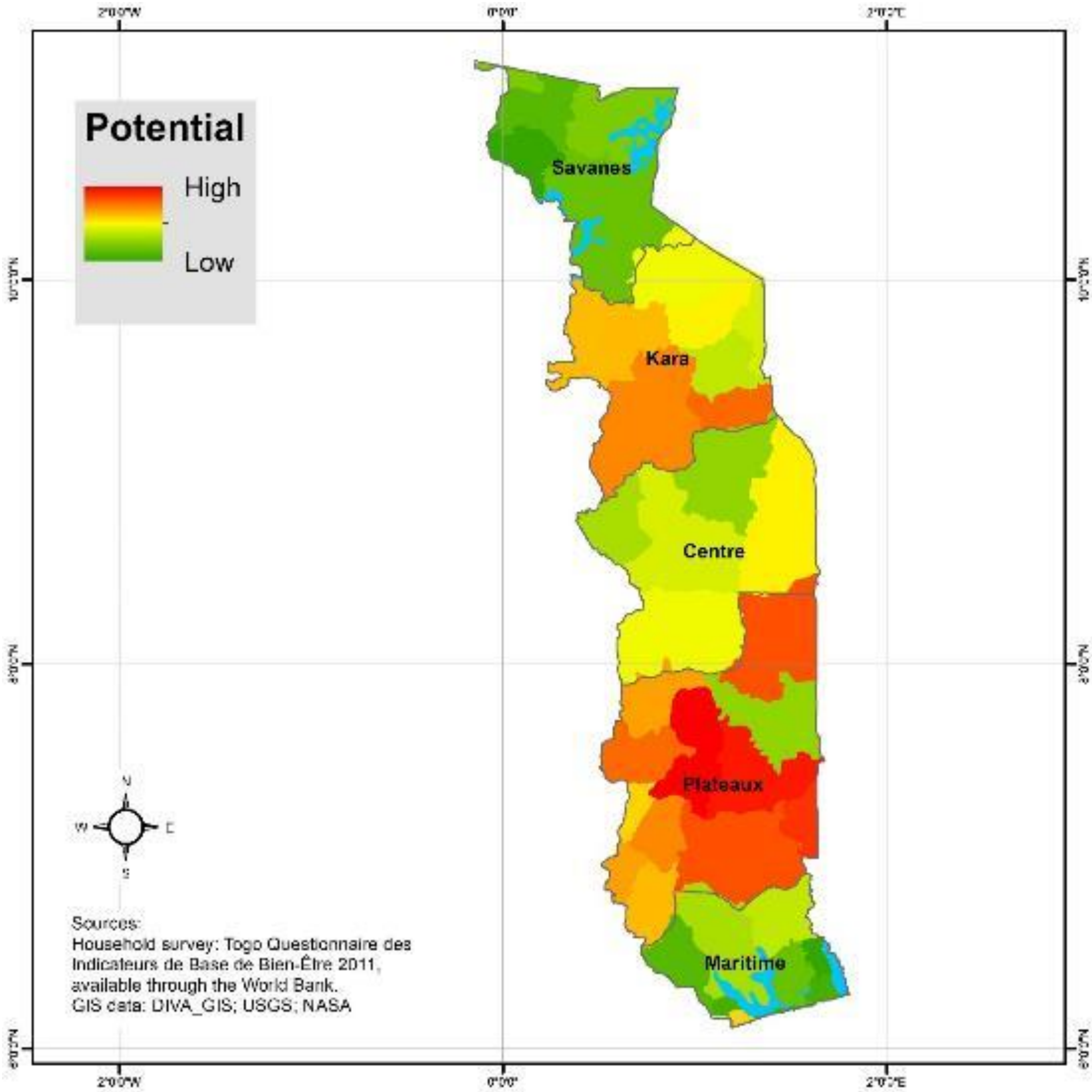

Figure 44: Togo: Agricultural potential

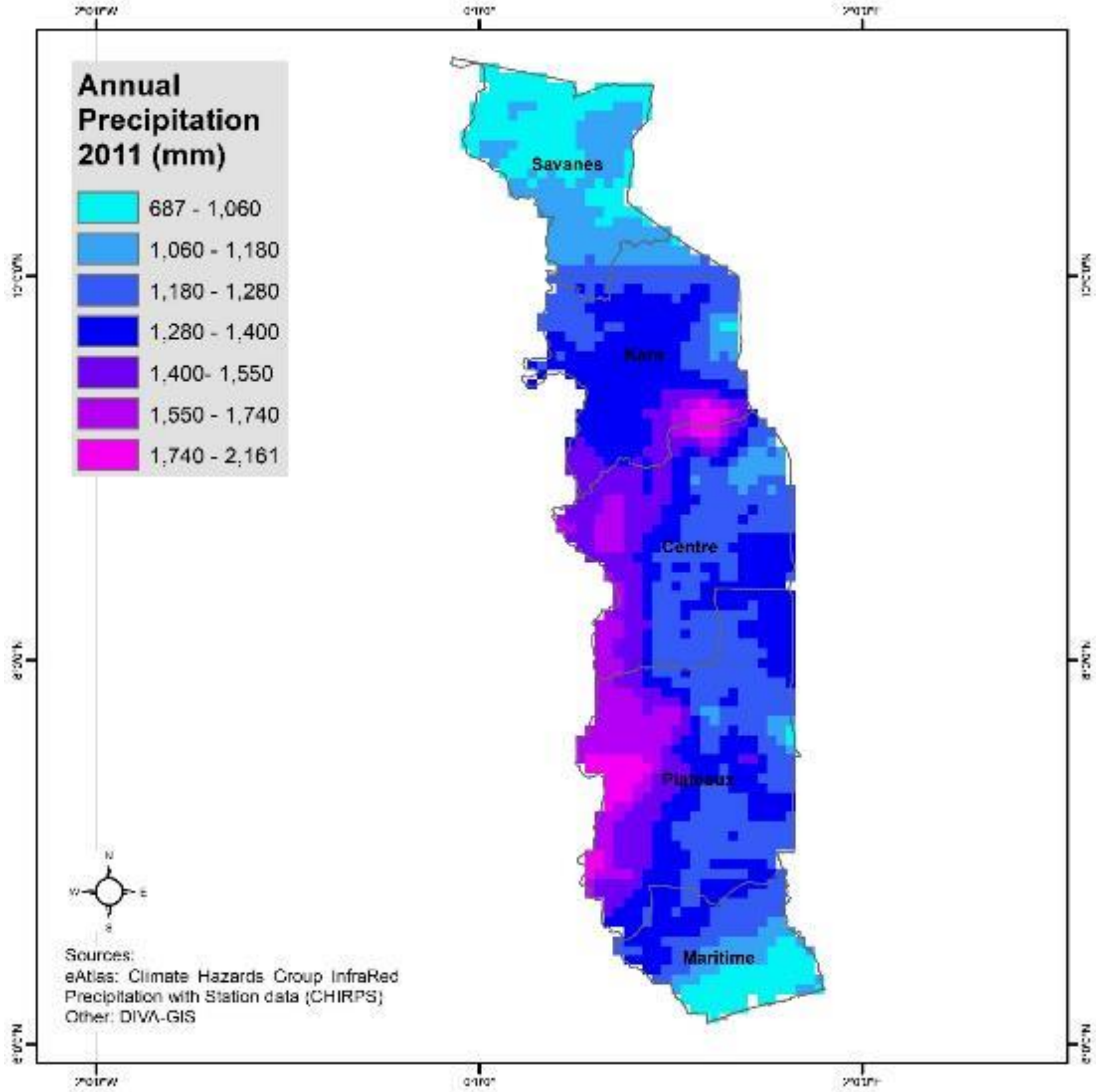

Figure 45: Togo: Annual precipitation (mm), 2011

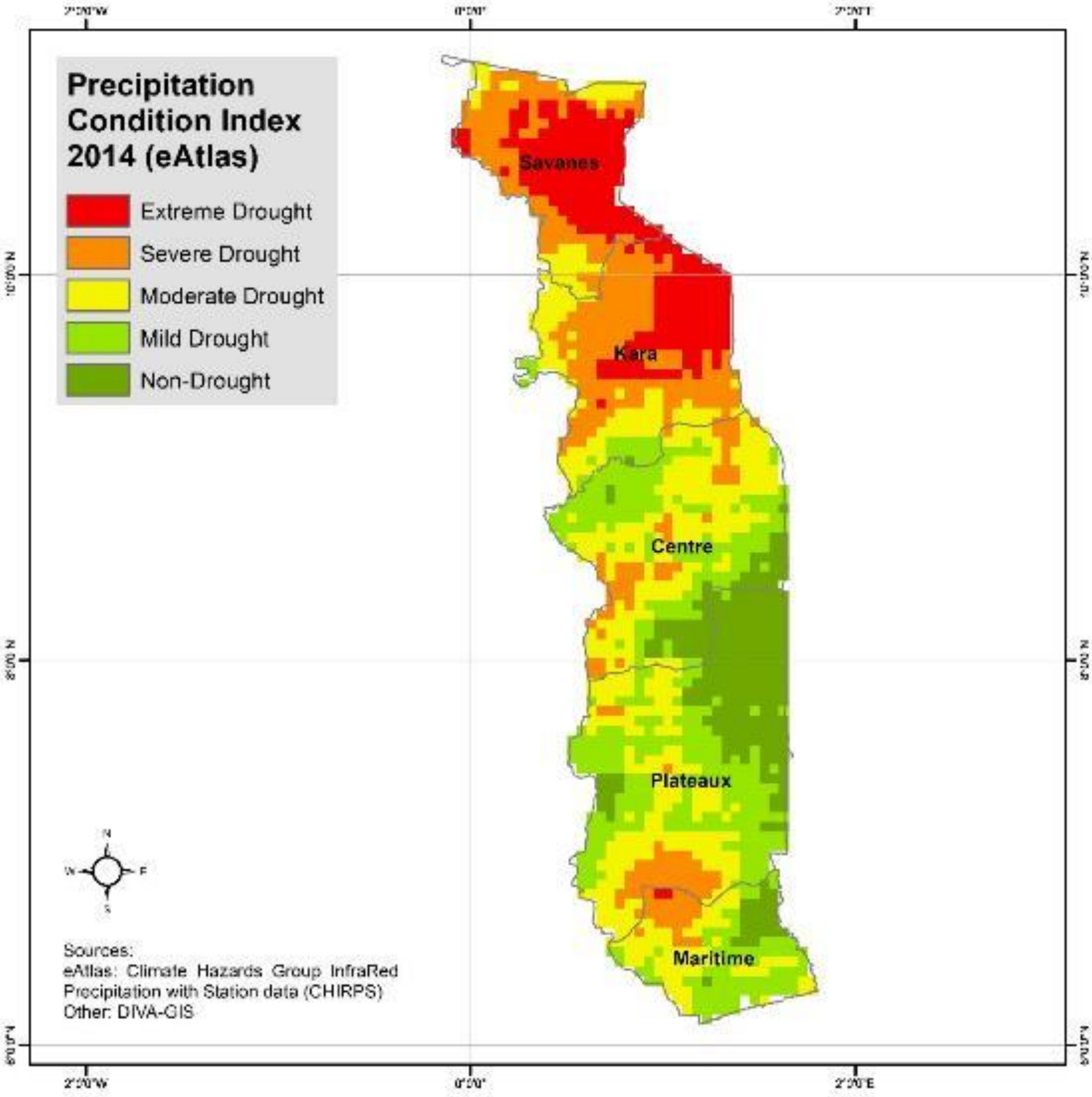

Figure 46: Togo: Precipitation condition index, 2014

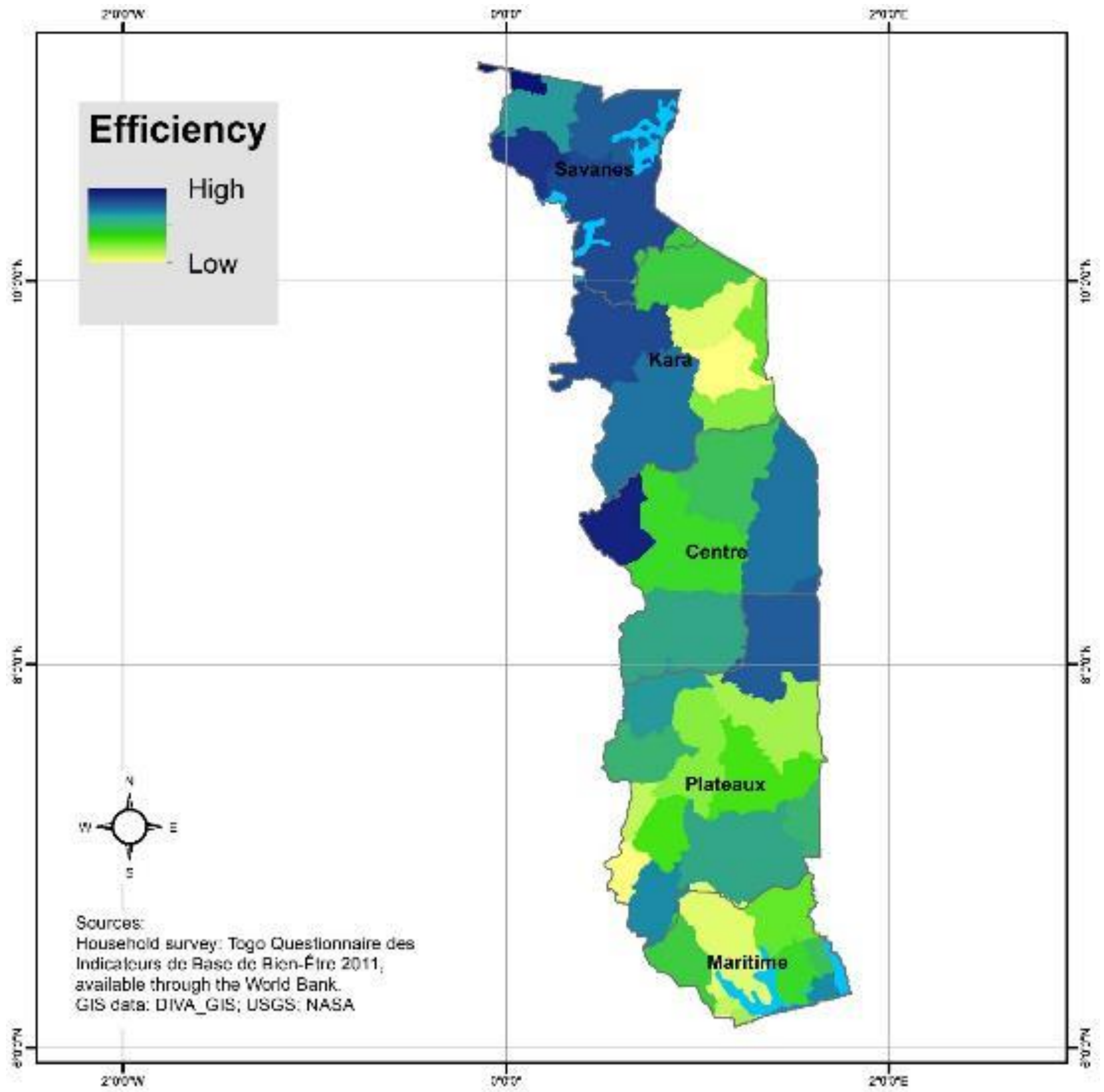

Figure 47: Togo: Agricultural efficiency

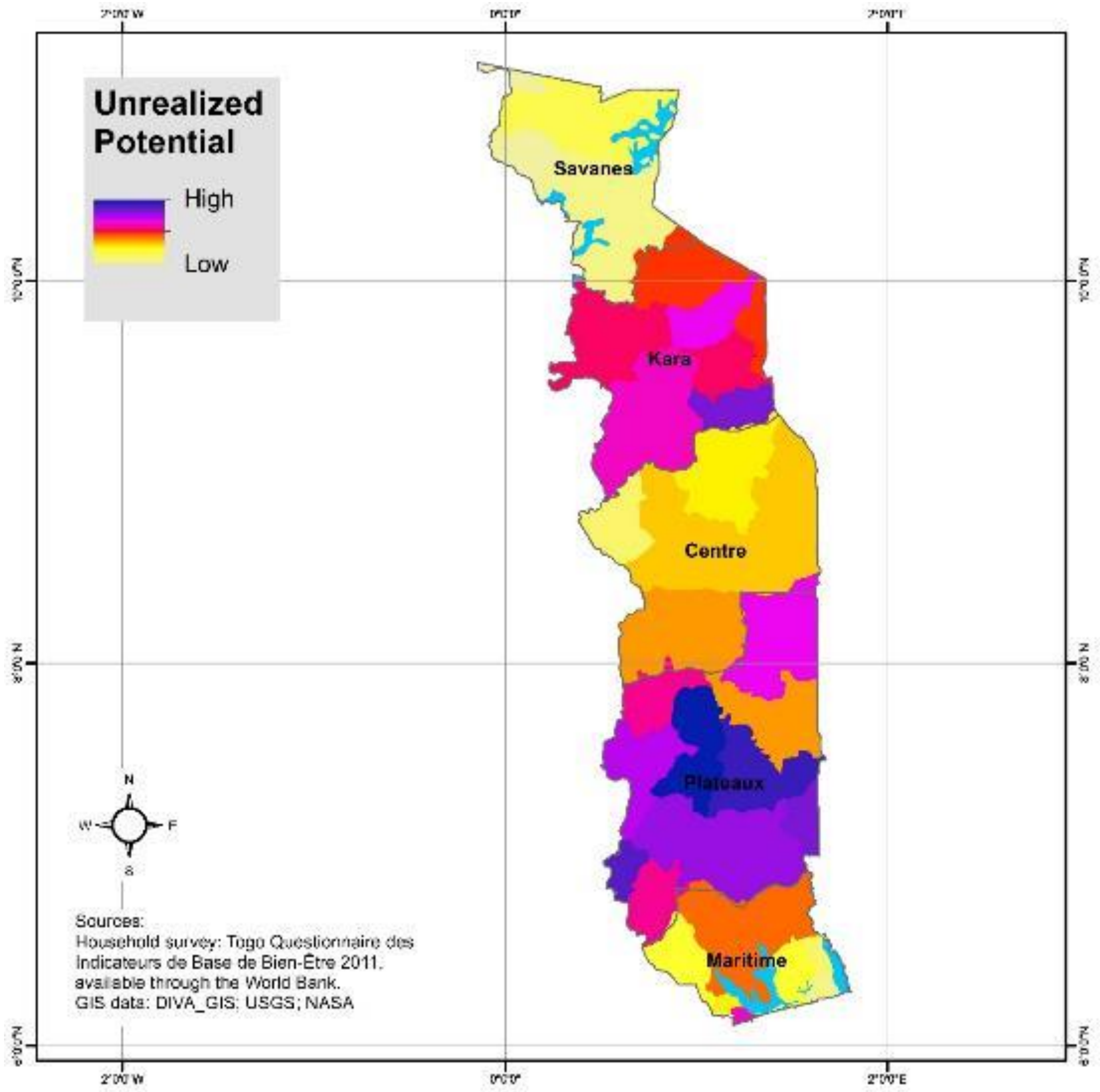

Figure 48: Togo: Unrealized agricultural potential

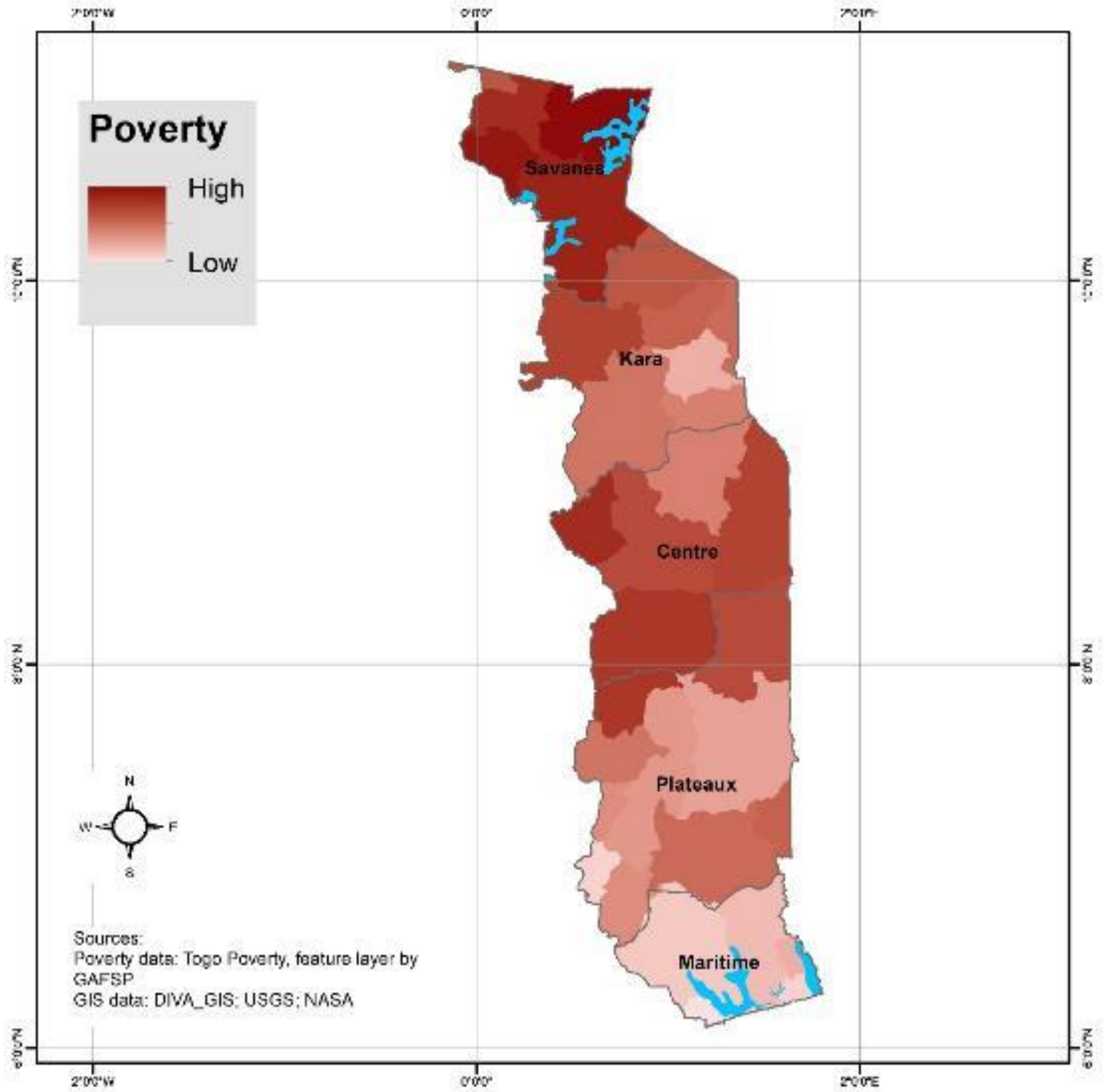

Figure 49: Togo: Poverty map

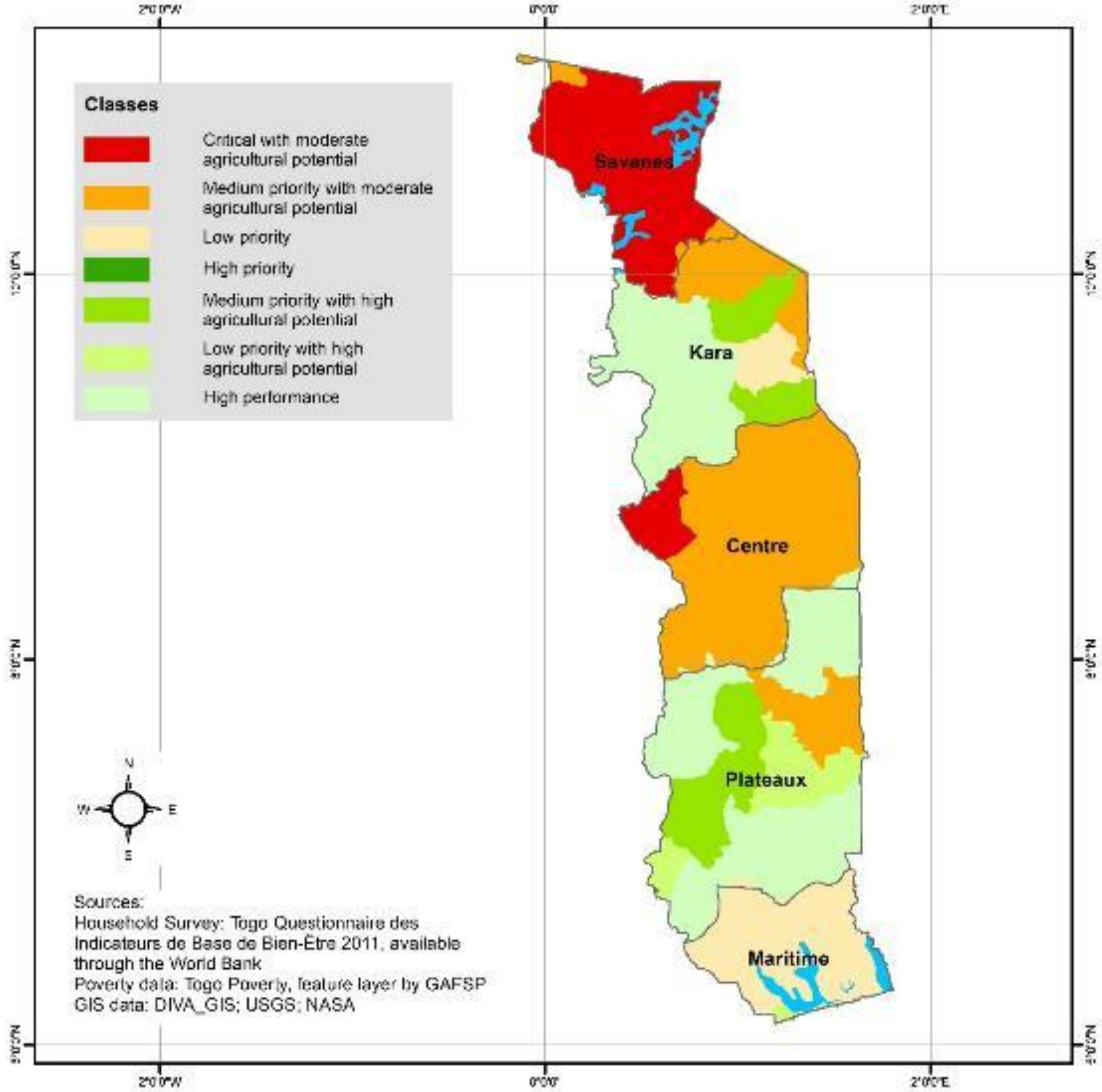

Figure 50: Togo: Agricultural typology

5.8 Zambia

The data sources used for the estimations and mapping for Zambia are:

- Household survey: The Living Conditions Monitoring Survey 2010, available through the Zambia National Data Archive and the World Bank. It has a sample of 20,000 households, out of which 7,865 are used for the frontier estimation, and is representative at the national, provincial, and urban/rural levels.
- Poverty data: Mapping Subnational Poverty in Zambia from the Central Statistics Office (2015).

Figure 51 shows the agricultural potential map for Zambia. The favorable agroecological conditions for maize and livestock in the Eastern region combined with the good access to urban markets explain the high agricultural potential of the Eastern region. The Southern region is also a large maize producer (Figure 52), but lower rainfall levels (Figure 53) explain its mix of medium to low potential. The high potential area covering the Central province results from a combination of high soil quality and an intermediate amount of rainfall. While the Northern Province has high rainfall and humidity, problems with soil acidity explain its overall lower agricultural potential, and the higher presence of areas suitable for potential enhancing innovations, as in the Western region, which is the driest part of the country.

The combination of potential with efficiency (Figure 54) produces the unrealized potential map in the central panel of Figure 55. While several regions of the map show areas with limited unrealized potential gaps, this is particularly problematic in the Western, Luapula, and Northern provinces where poverty levels are high (Figure 56).

The agricultural typology is shown in Figure 57. High poverty rates and low agricultural potential explain the areas in the critical (red) class in the Western, Luapula, and Northern provinces. Located east from both of these critical areas are high priority zones, while also suffering from high poverty offer large unrealized potential gaps. The central stretch of the country (Copperbelt, Central, Lusaka, and Southern provinces) fall into the high performance or low priority classes. In general, a mix of efficiency enhancing and potential enhancing innovations appear to be necessary in the east and west of the country to tackle their higher poverty rates.

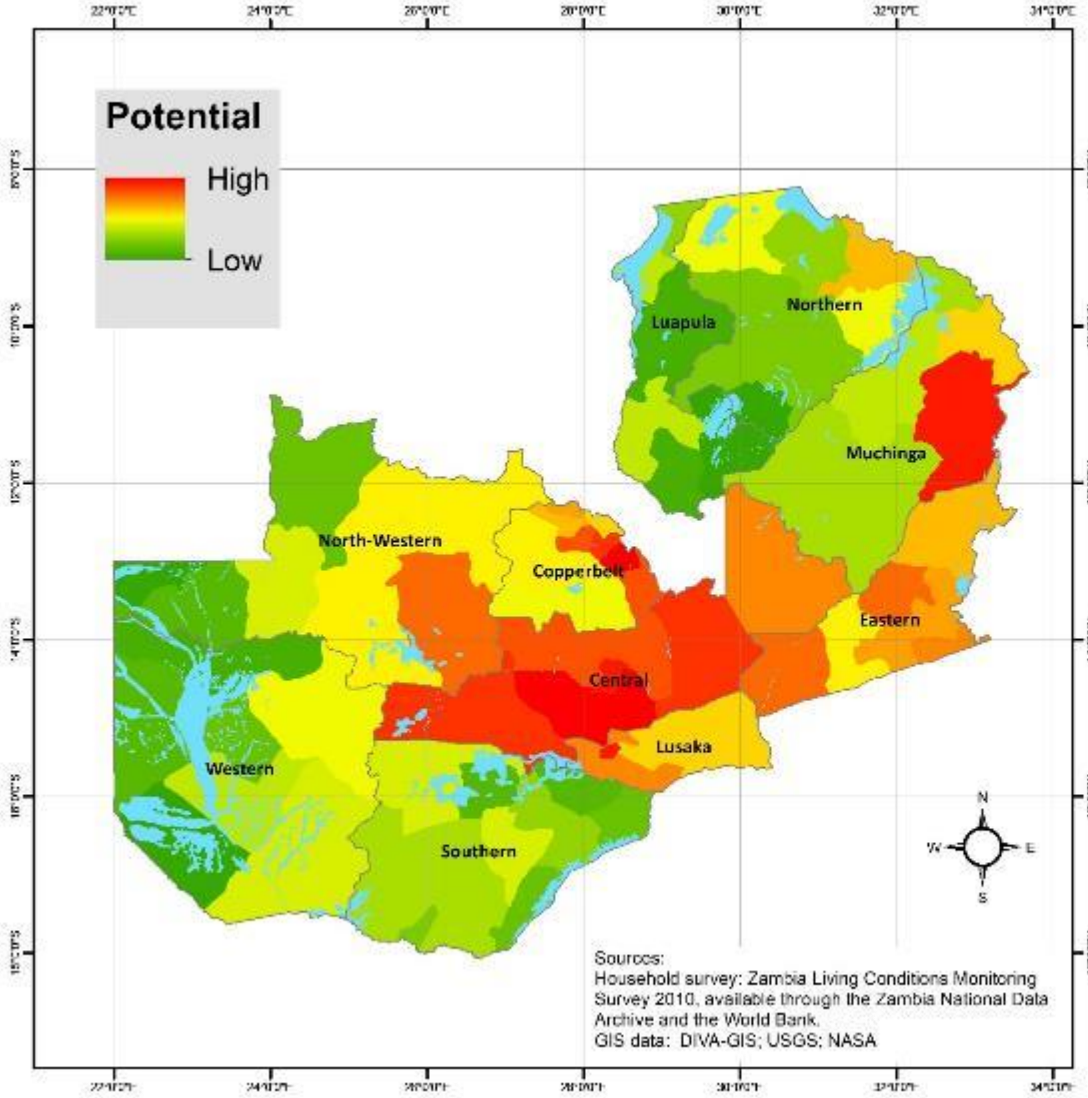

Figure 51: Zambia: Agricultural potential

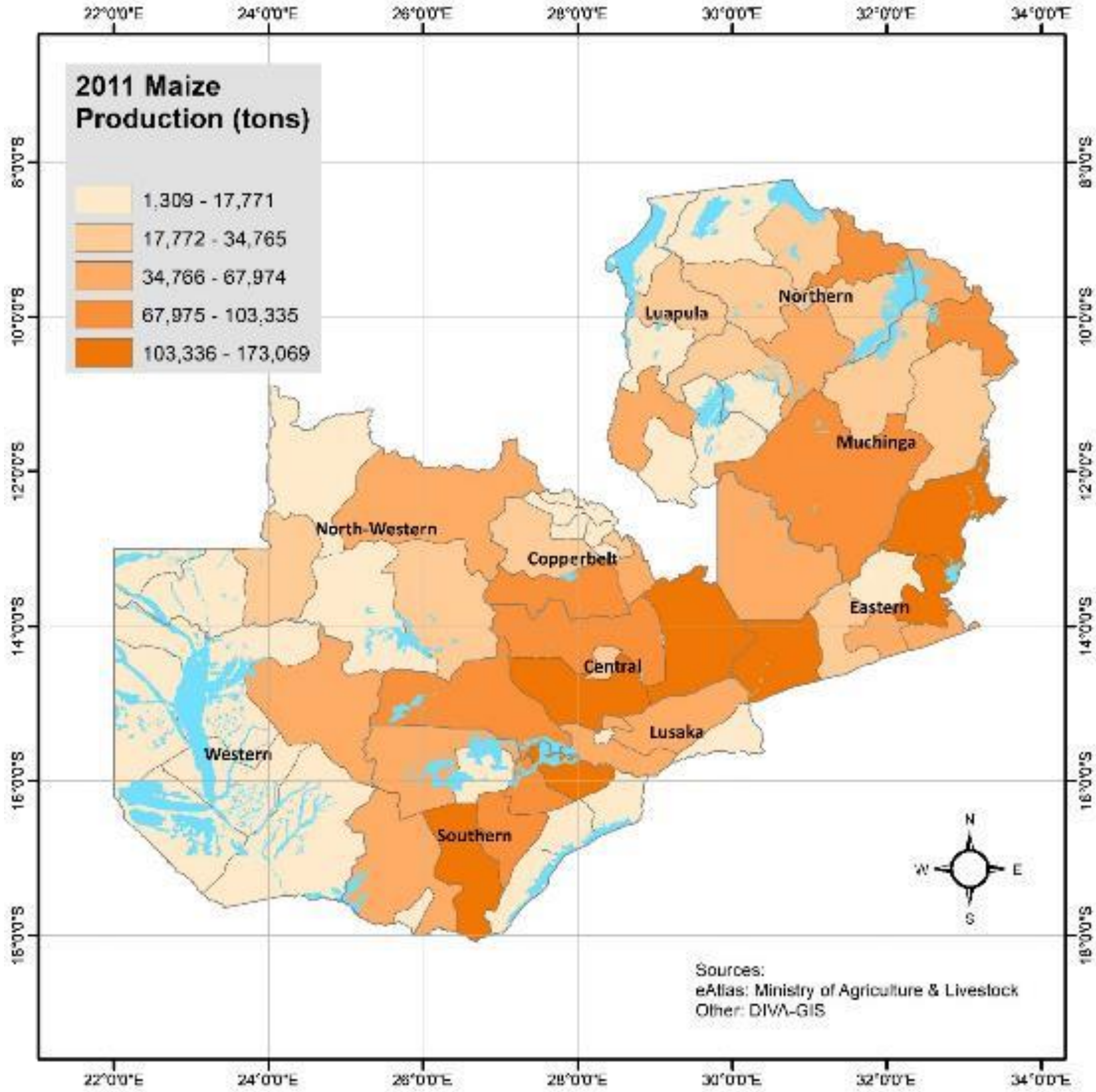

Figure 52: Zambia: Maize production (tons), 2011

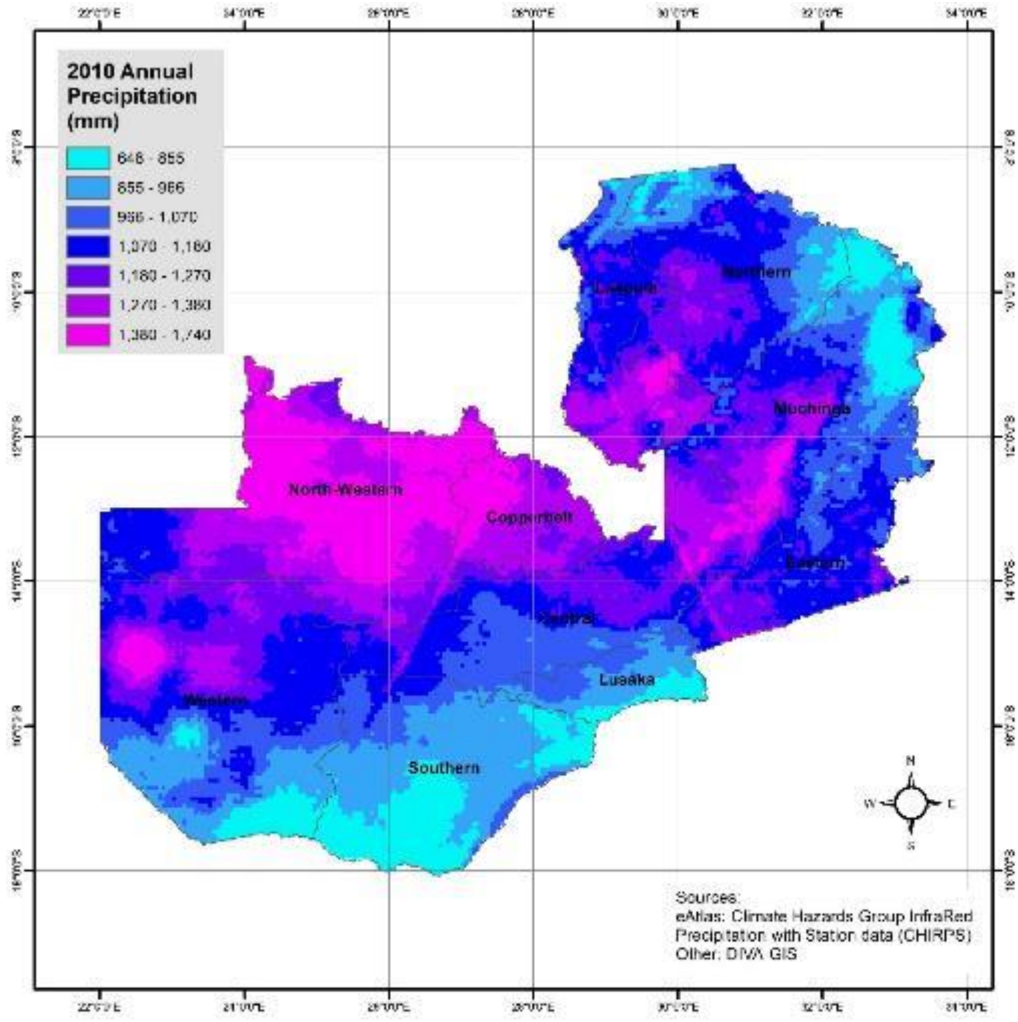

Figure 53: Zambia: Annual precipitation (mm), 2010

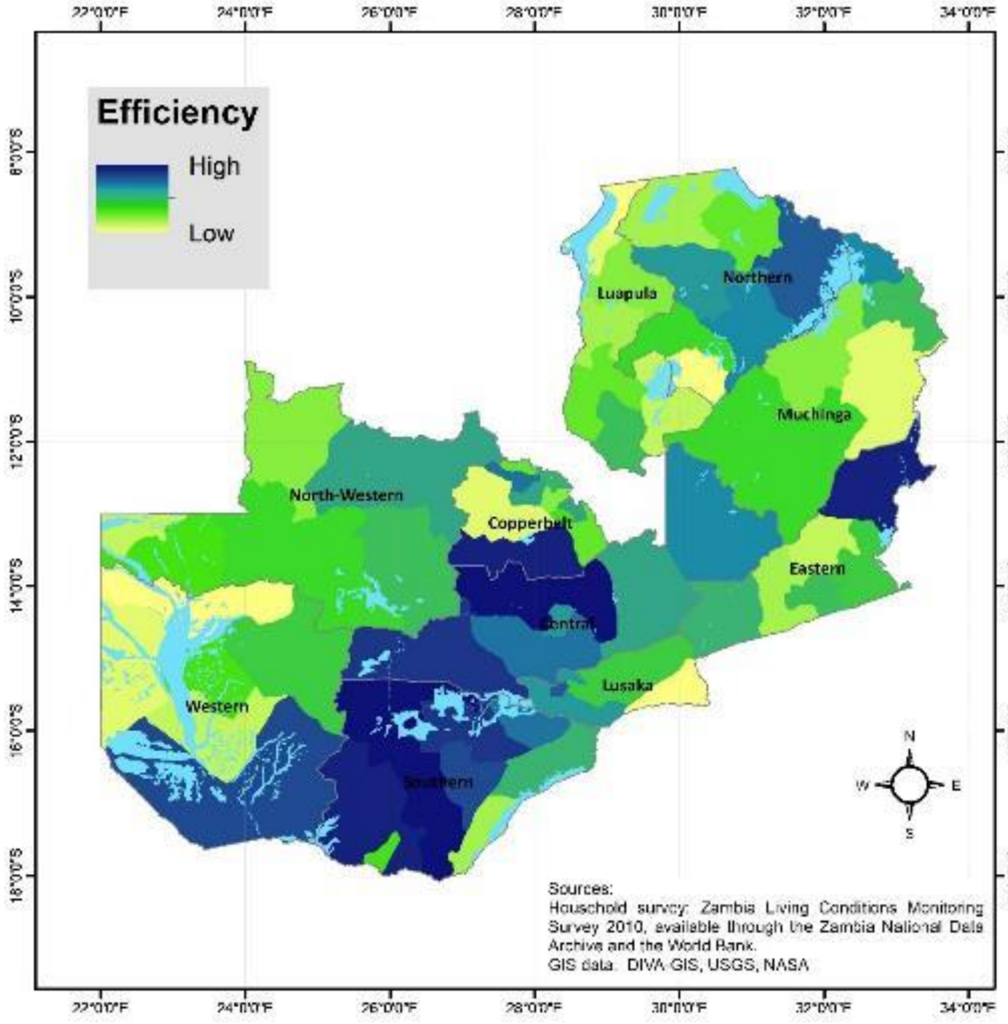

Figure 54: Zambia: Agricultural efficiency

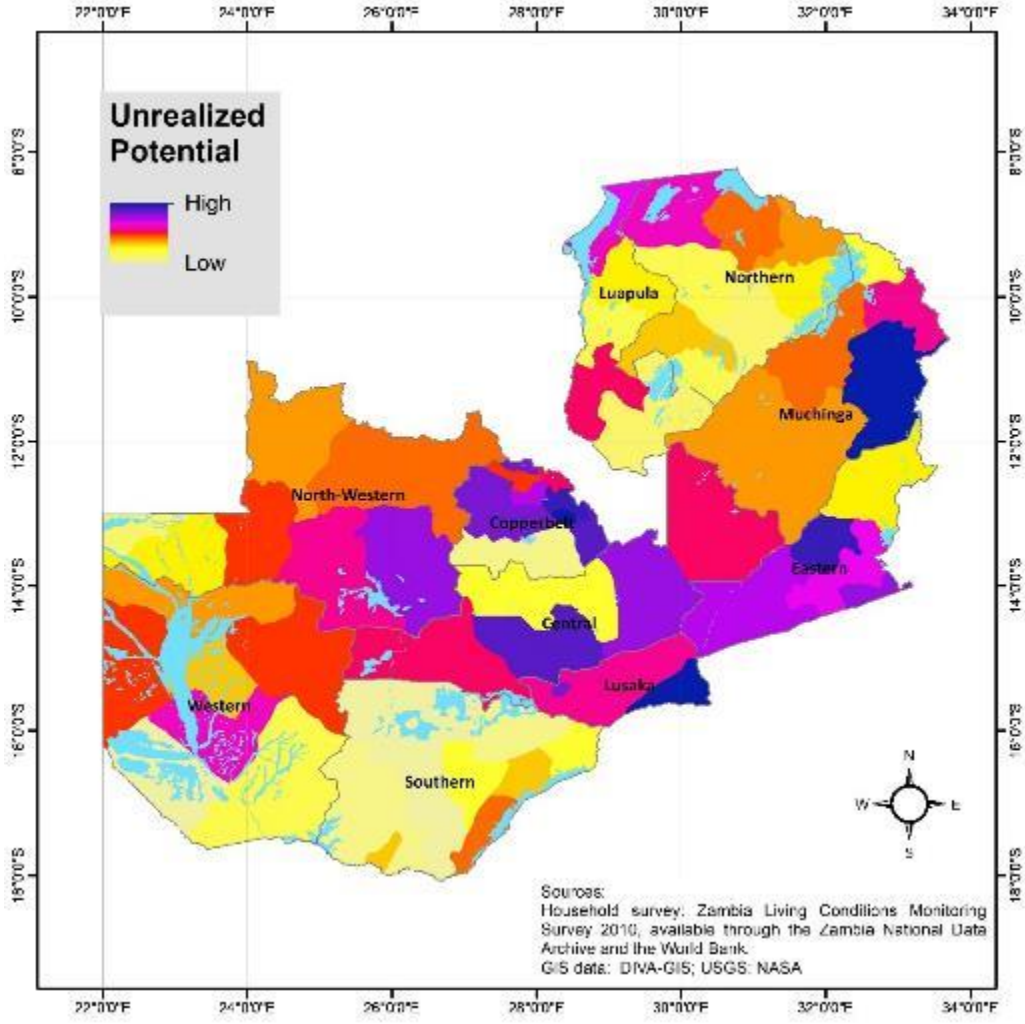

Figure 55: Zambia: Unrealized agricultural potential

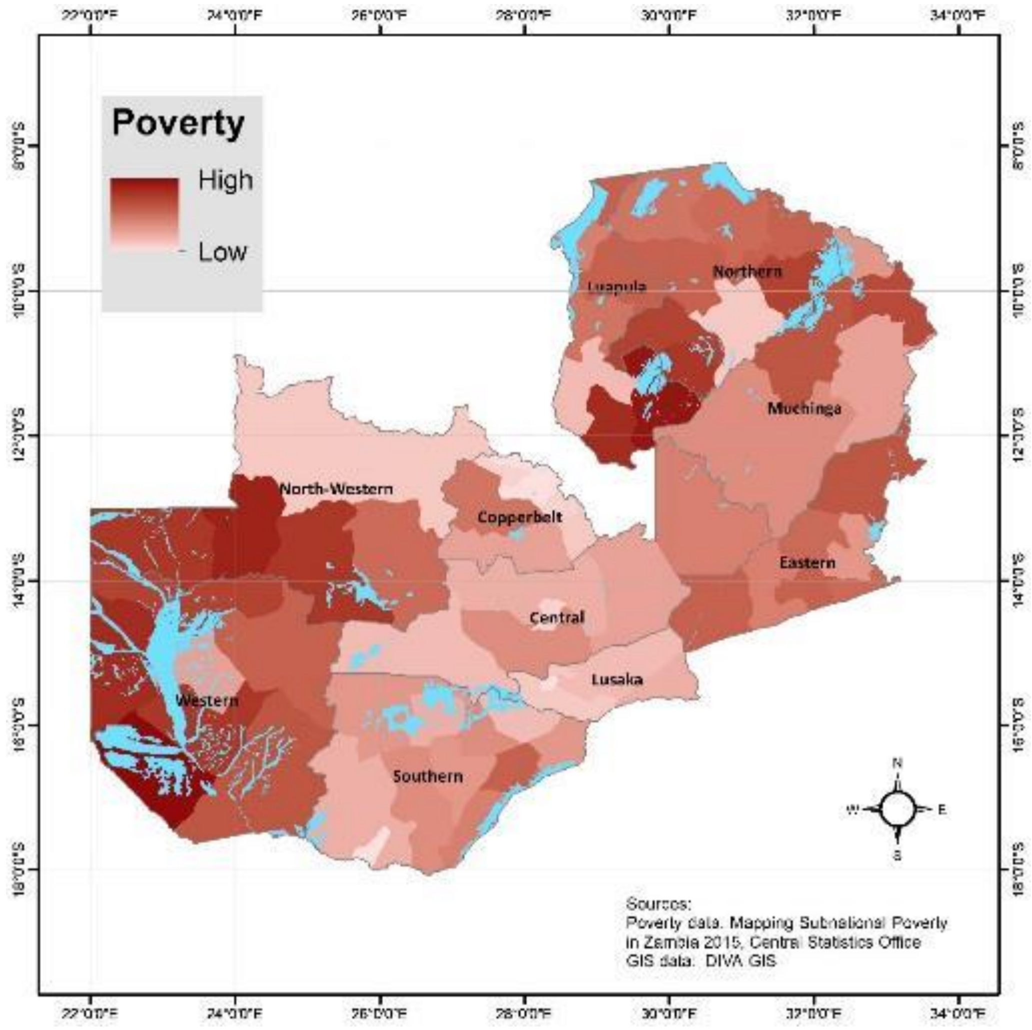

Figure 56: Zambia: poverty map

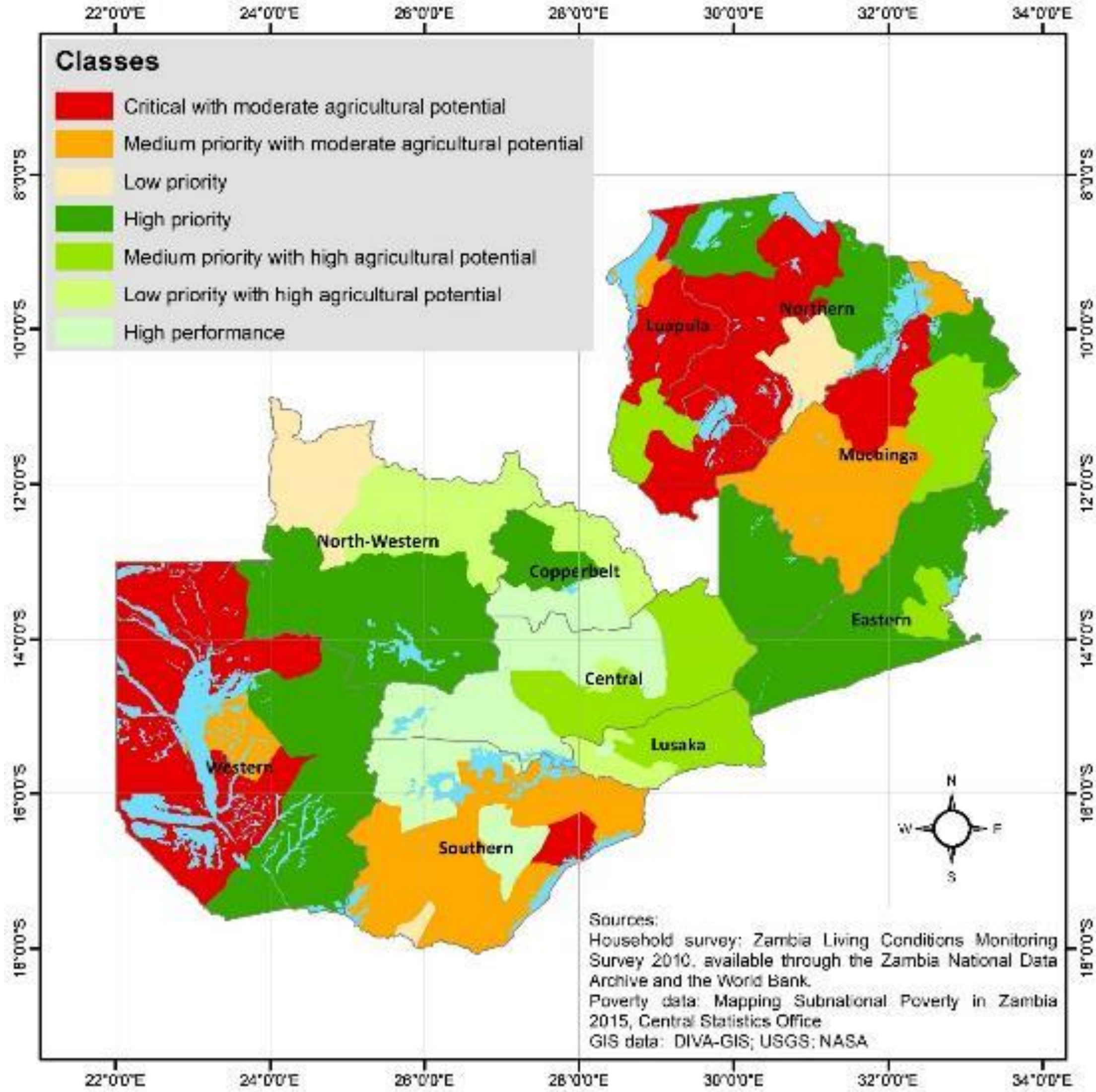

Figure 57: Zambia: Agricultural typology

6 Concluding remarks

PARI's main goal is to contribute to sustainable agricultural growth and food security in Africa and India by supporting the scaling of proven innovations in the agri-food sector in collaboration with all relevant actors. Agricultural development depends on innovation, which is the result of a complex system of interactions that takes place in an environment characterized by its multidimensional nature (biophysical, technological, sociocultural, economic, institutional, and political). Understanding the biophysical and economic dimensions of the environment in which agriculture and agricultural innovation take place requires an approach that combines economic, statistical, and spatial analysis tools.

Several of the studies have linked agricultural potential and need-based criteria to target development oriented investments by combining agroecological and poverty data, but have ignored the role markets play in the process of innovation. For investments in agricultural innovation to be sustainable, farm-level increases in productivity need to be translated into higher incomes and better livelihoods for rural households. Our proposed approach attempts to bridge that gap by mapping estimates of agricultural potential and efficiency under the framework of production theory applied to agriculture by combining agroecological, poverty, market, and farm-level information.

The idea behind the concept of agricultural innovation is to allow agricultural education, research, and extension to contribute substantially to enhance agricultural production and reduce rural poverty. Hence, when deciding where to invest and introduce innovations in agriculture, priority should be given to areas where rural poverty is high and increases in agricultural production would be more beneficial. However, high poverty areas can be very heterogeneous both in terms of what their current agricultural potential is, and how much of it farmers are able to attain by operating efficiently.

In our setup, we do not only consider as agricultural innovations those paradigm-shifting technological changes that dramatically increase agricultural potential, but also the smaller innovations that allow smallholders to catch up to their peers and larger farmers by helping them overcome the specific challenges they face. Implicit in this setup, is the idea that there exists a maximum or optimum level farmers can catch up to with smaller innovations of their own and their peers (and hence become more efficient), and an upper bound (which we call potential) that can be increased by larger investments in R&D with the support of governments, donors, and researchers.

The SFA approach allows the econometric exploration of the notion that, given the fixed local agroecological and economic conditions in a micro-region and the occurrence of random shocks that affect agricultural production (weather, prices, etc.), the investment, production decisions and technological innovations a farmer makes translate into higher or lower production and income. In such a context, inefficiency is defined as the loss incurred in by operating away from the frontier given the current prices and fixed factors faced by the household. By estimating where the frontier lies, and how far each producer is from it, the stochastic frontier approach helps to identify local potential and efficiency levels to construct the typology.

Our series of maps for the eight different countries included in this study (Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Nigeria, Togo, and Zambia) highlight the degree of heterogeneity in the potential and efficiency levels of agriculture across and within countries. Our analysis recognizes that different types of innovation approaches are necessary for areas in which farmers are operating close to their maximum potential or far from it, and identifies areas in which investments are more necessary to alleviate poverty. While the goal for this report was to create a consistent set of results and maps for all 8 countries, our hope is that through AGRODEP and the network of country partners in PARI, we can extend and enrich this work by focusing this methodology to specific countries, regions, and value chains to better identify efficiency bottlenecks and match them with relevant solutions and innovations.

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Appendix 1: SFA estimation results

Table 5: Ethiopia: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Sorghum	-0.367	0.199*
Teff	-0.199	0.093**
Wheat	0.574	0.247**
Sesame	-0.321	0.234
Banana	-0.235	0.089***
Chat	0.217	0.067***
Coffee	0.275	0.109**
Oxen	0.509	0.281*
Cow	-0.558	0.242**
Male Goat	- 0.237	0.236
Female Goat	0.963	0.390**
Ram	0.019	0.288
Ewe	-0.647	0.288**
Cock	0.232	0.187
Hen	-0.073	0.252
Land Use		
Evergreen forests	0.495	0.255*
Closed Shrubland	-2.570	2.454
Open Shrubland	-0.894	0.314***
Woody Savanna	-1.408	0.310***
Savanna	0.429	0.229*
Grassland	0.137	0.282
Cropland	0.019	0.235
Barren, Urban, and Wetlands	0.766	0.453*
Constant	6.017	2.161***
$ln\sigma_v$		
Constant	0.362	0.113***
$ln\sigma_u^2$		
Land	-0.000	0.000***
Number of Sickles	-0.035	0.082
Number of Axes	-0.289	0.108***
Number of Pick Axes	-0.020	0.030
Number of Traditional Ploughs	-0.301	0.118**
Household size	-0.072	0.040*
Time to Market	0.011	0.015
Female Head	0.190	0.166
Maximum Schooling	-0.041	0.021**
Constant	2.172	0.209***
σ_v	1.198	0.068
N		2,786
chi2		143.11

Table 6: Ghana: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Cocoa	-0.176	0.117
Cassava	-0.289	0.102***
Plantain	- 0.257	0.114**
Yam	-0.196	0.097**
Cattle	0.186	0.169
Sheep	0.105	0.155
Goats	1.054	0.221***
Pigs	-0.324	0.108***
Chicken	0.619	0.117***
Fish	- 0.028	0.036
Land Use		
Evergreen Needlelead forest	0.644	0.144***
Woody savannas	-0.132	0.229
Savannas	0.347	0.095***
Grasslands and Shrublands	-1.161	0.471**
Croplands	-0.321	0.566
Barren, Urban, and Wetlands	2.123	0.613***
Constant	1.327	0.866
$ln\sigma_v$		
Constant	0.488	0.034***
$ln\sigma_u^2$		
Land	-0.262	0.018***
Log farm assets	-0.159	0.023***
Household size	-0.030	0.016**
Time to Market	-0.059	0.031*
Female Head	0.252	0.078***
Maximum Schooling	-0.009	0.009
Constant	2.173	0.124***
σ_v	1.277	0.022
N		7,262
chi2		148.62

Table 7: Kenya: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Maize	-0.370	0.168**
Potato	-0.185	0.083**
Bean	-0.157	0.088*
Tea	0.059	0.088
Coffee	0.312	0.090**
Exotic Dairy Cattle	-0.608	0.158***
Zebu Milk Cattle	0.664	0.130***
Zebu Beef Cattle	-0.138	0.134
Wool Sheep	0.877	0.131***
Goat	0.425	0.144***
Chicken	0.133	0.151
Land Use		
Evergreen Broadleaf forest	4.123	0.566***
Shrublands	1.879	0.192***
Woody savannas	0.246	0.388
Savannas	0.432	0.197**
Grasslands	0.470	0.125***
Croplands	-1.971	0.599***
Barren, Urban, and Wetlands	-4.271	1.078***
Constant	1.201	1.186
$ln\sigma_v$		
Constant	0.678	0.030***
$ln\sigma_u^2$		
Land	-0.665	0.087***
Log farm assets	-0.111	0.027***
Household size	-0.065	0.019***
Time to Market	-0.187	0.049***
Female Head	0.575	0.088***
Maximum Schooling	-0.046	0.013***
Constant	2.143	0.166***
σ_v	1.403	0.021
N		6,049
chi2		575.71

Table 8: Malawi: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Tobacco	0.313	0.097***
Groundnut	0.046	0.080
Rice	-0.240	0.228
Soy	0.449	0.147***
Cotton	-0.312	0.138**
Tomato	0.226	0.068***
Cow	-1.637	0.327***
Goat	0.295	0.187
Pig	0.648	0.121***
Hen	0.559	0.122***
Cock	-0.491	0.157***
Duck	0.885	0.235***
Land Use		
Deciduous and other forest	-2.112	0.916**
Woody savannas	0.398	0.247
Savannas	0.293	0.202
Croplands	0.255	1.026
Barren, Urban, and Wetlands	-0.002	0.880
Constant	10.216	1.956***
$ln\sigma_v$		
Constant	0.461	0.029***
$ln\sigma_u^2$		
Land	-0.735	0.076***
Log farm assets	-0.405	0.040***
Household size	0.021	0.020
Time to Market	0.003	0.022
Female Head	0.301	0.080***
Maximum Schooling	-0.052	0.012***
Constant	3.380	0.170***
σ_v	1.259	0.018
N		5,822
chi2		445.51

Table 9: Nigeria: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Beans	0.445	0.249*
Cassava	0.328	0.080***
Groundnuts	-0.071	0.116
Sorghum	-0.628	0.242***
Yam	0.135	0.060**
Goat	0.266	0.157*
Sheep	0.931	0.137***
Chicken	-0.883	0.175***
Land Use		
Evergreen forest and Shrublands	1.172	0.260***
Woody savannas	0.553	0.226**
Savannas	0.317	0.274
Grasslands	-0.611	0.363*
Croplands	-0.199	0.137
Barren, Urban, and Wetlands	0.710	1.020
Constant	3.351	0.672***
$ln\sigma_v$		
Constant	0.274	0.106***
$ln\sigma_u^2$		
Land	-1.074	0.564*
Log farm assets	-0.223	0.054***
Household size	-0.076	0.027***
Time to Market	0.000	0.040
Female Head	-0.069	0.168
Maximum Schooling	-0.019	0.016
Constant	2.278	0.287***
σ_v	1.147	0.061
N		2,162
chi2		448.22

Table 10: Togo: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Sorghum	0.541	0.106***
Yam	0.100	0.023***
Cassava	0.091	0.027***
Beans	0.245	0.112**
Peanuts	0.065	0.072
Land Use		
Woody Savannas, Urban, Wetlands, and Barren	0.834	0.152***
Savannas	-0.243	0.126*
Shrublands and Grasslands	-0.397	0.701
Croplands	0.352	0.975
Constant	6.844	0.470***
$ln\sigma_v$		
Constant	0.240	0.332
$ln\sigma_u^2$		
Land	-0.002	0.003
Household size	-0.222	0.164
Time to Market	0.084	0.091
Female Head	0.924	0.448**
Maximum Schooling	0.053	0.034
Constant	0.782	0.623
σ_v	1.128	0.187
N		2,739
chi2		217.11

Table 11: Zambia: Agricultural revenue SFA estimation results

ln(Farm Revenue)	Coeff.	Std. Error
Prices		
Hybrid Maize	-0.050	0.163
Cassava	-0.035	0.095
Beans	-0.398	0.123***
Sweet Potato	0.123	0.066*
Groundnuts	0.106	0.053**
Live Cattle	0.676	0.110***
Slaughtered Cattle	-0.893	0.125***
Live Goat	-0.694	0.141***
Slaughtered Goat	1.391	0.285***
Live Pig	-0.023	0.105
Chicken	0.581	0.096***
Land Use		
Woody savannas	-4.365	0.838***
Savannas	-4.090	0.841***
Forests, Grasslands, and Shrublands	-7.709	1.108***
Barren, Urban, and Wetlands	-5.018	1.037***
Constant	8.454	1.229***
$ln\sigma_v$		
Constant	0.310	0.028***
$ln\sigma_u^2$		
Land	-1.410	0.086***
Log farm assets	-0.275	0.029***
Household size	-0.016	0.016
Time to Market	0.033	0.026
Female Head	0.203	0.080**
Maximum Schooling	-0.109	0.013***
Constant	3.210	0.164***
σ_v	1.168	0.017
N		7,865
chi2		347.63

Appendix 2: Accessibility maps

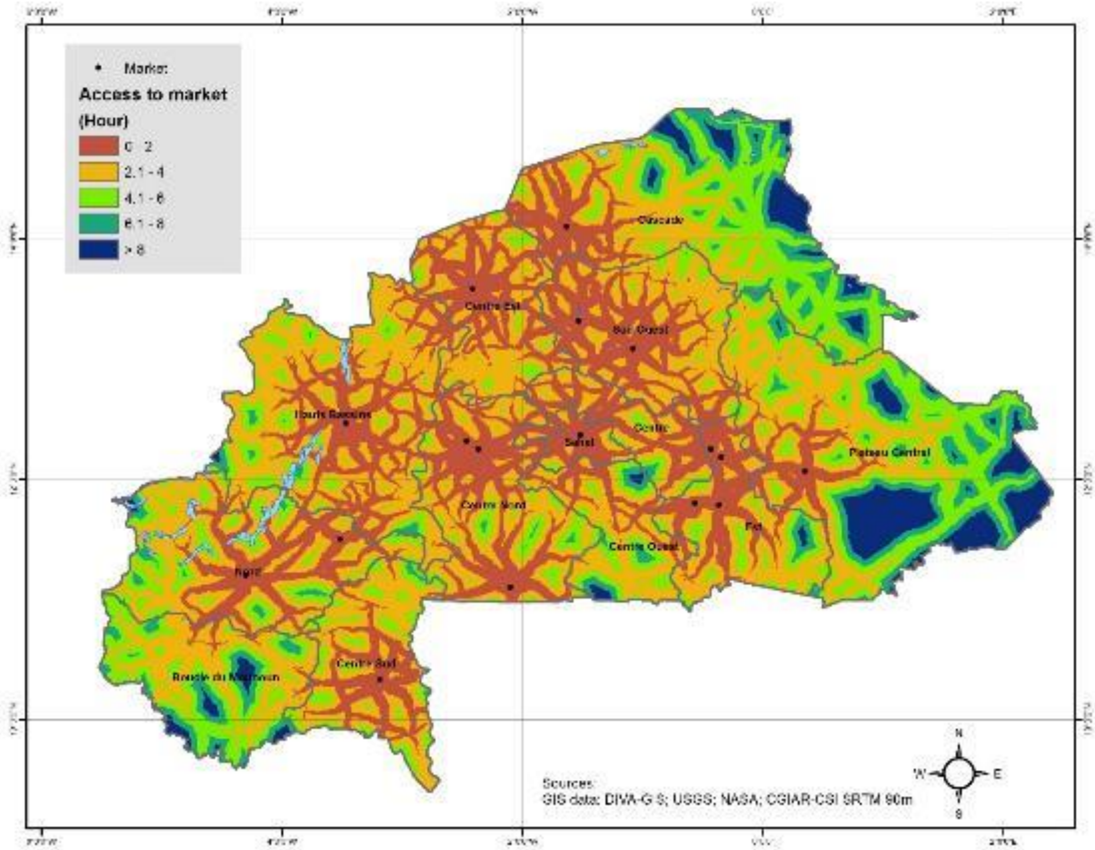

Figure 58: Burkina Faso: Accessibility

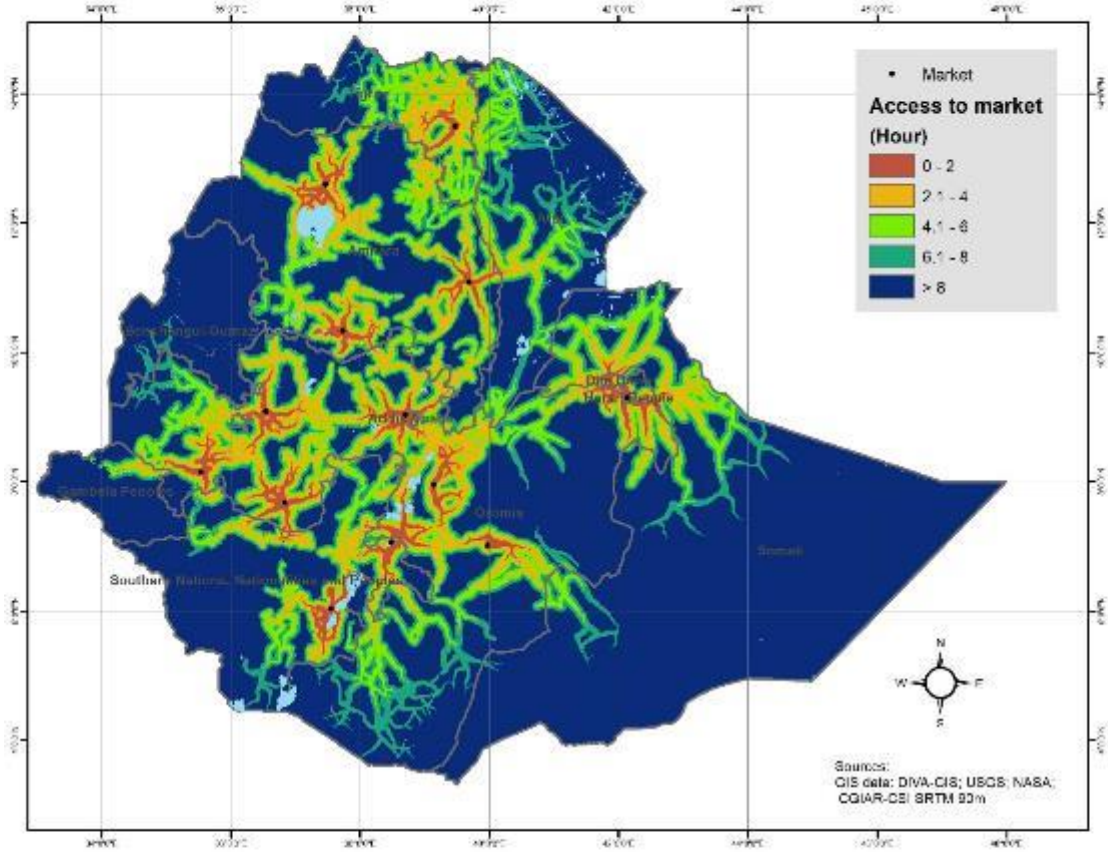

Figure 59: Ethiopia: Accessibility

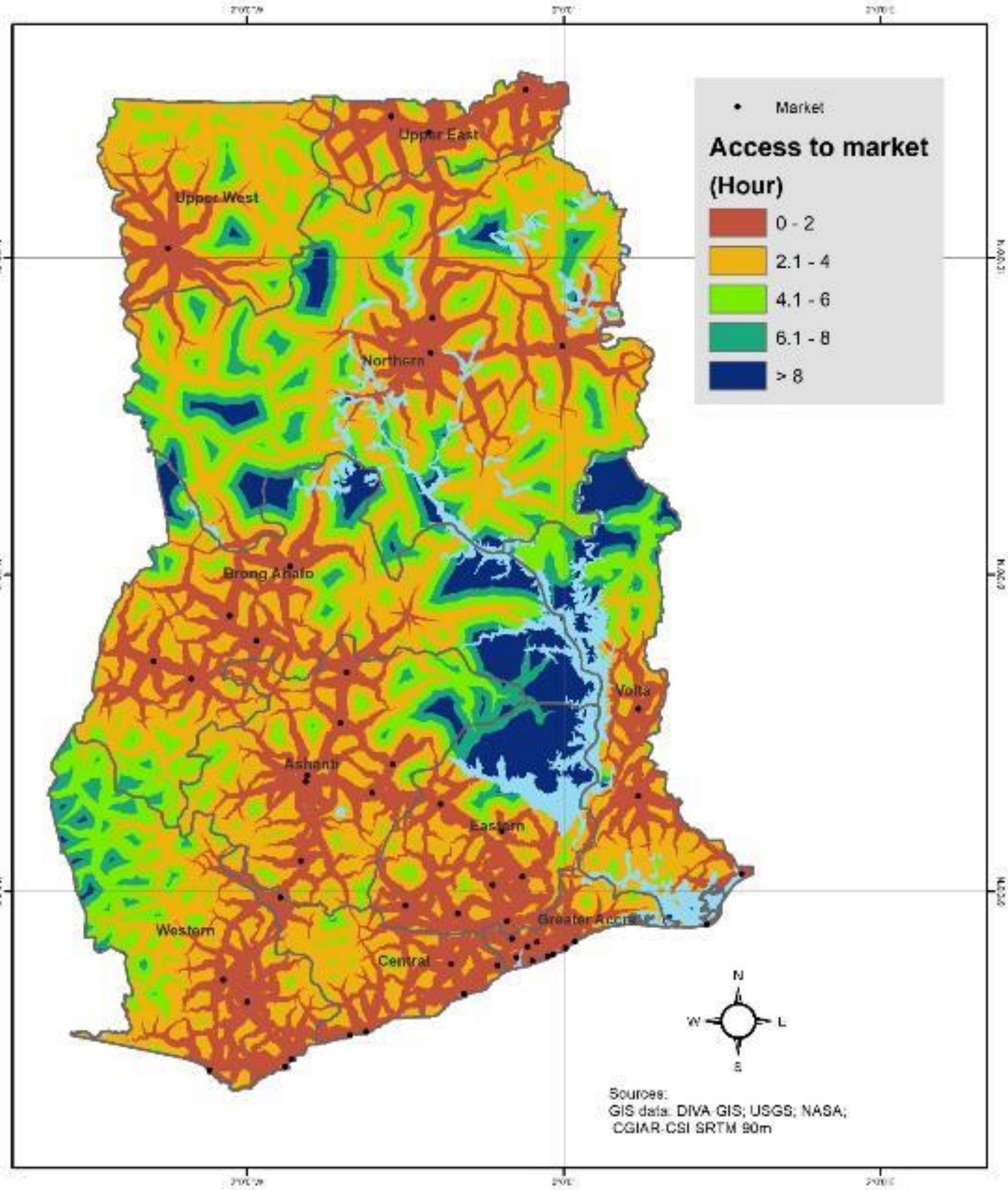

Figure 60: Ghana: Accessibility

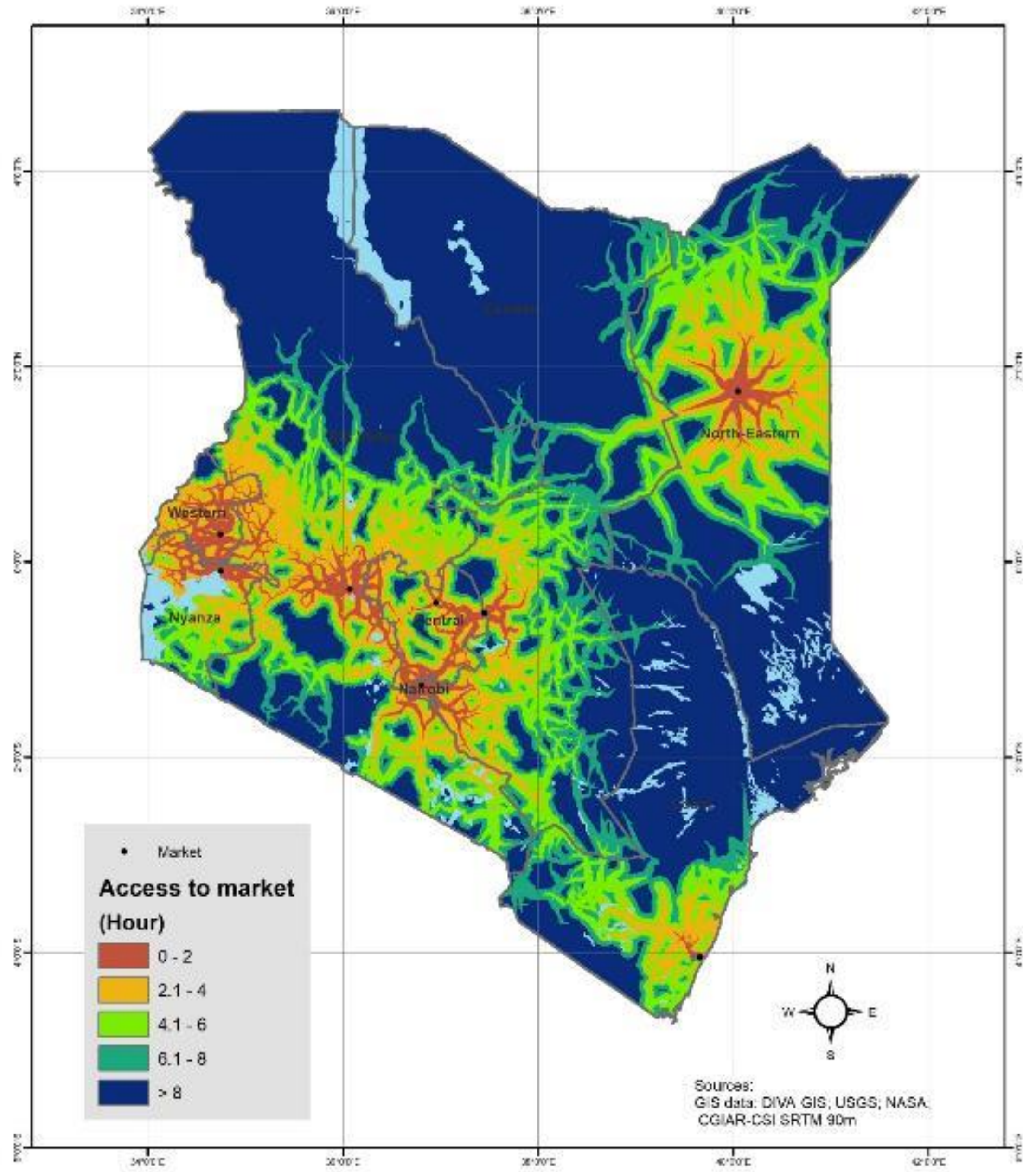

Figure 61: Kenya: Accessibility

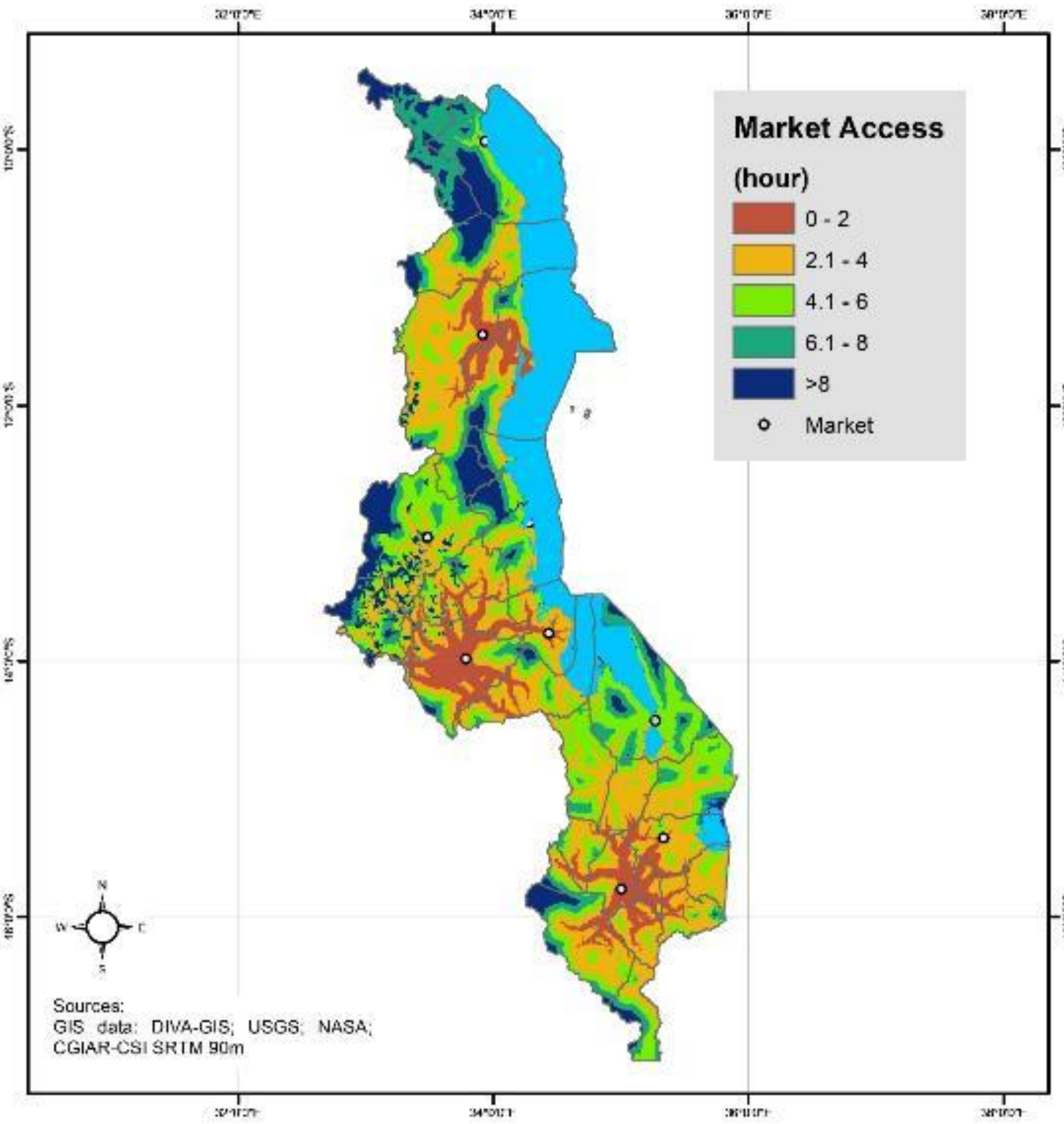

Figure 62: Malawi: Accessibility

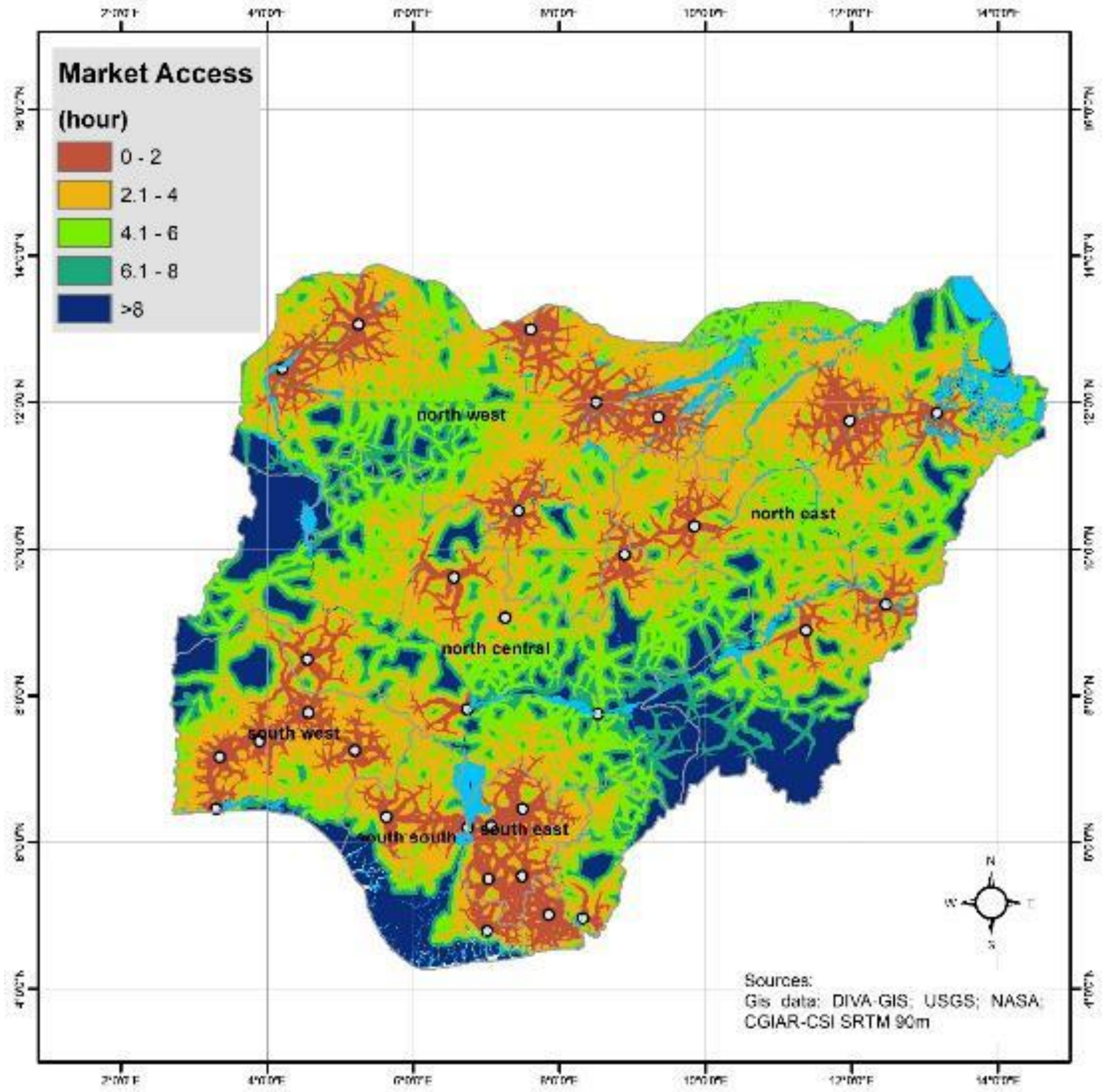

Figure 63: Nigeria: Accessibility

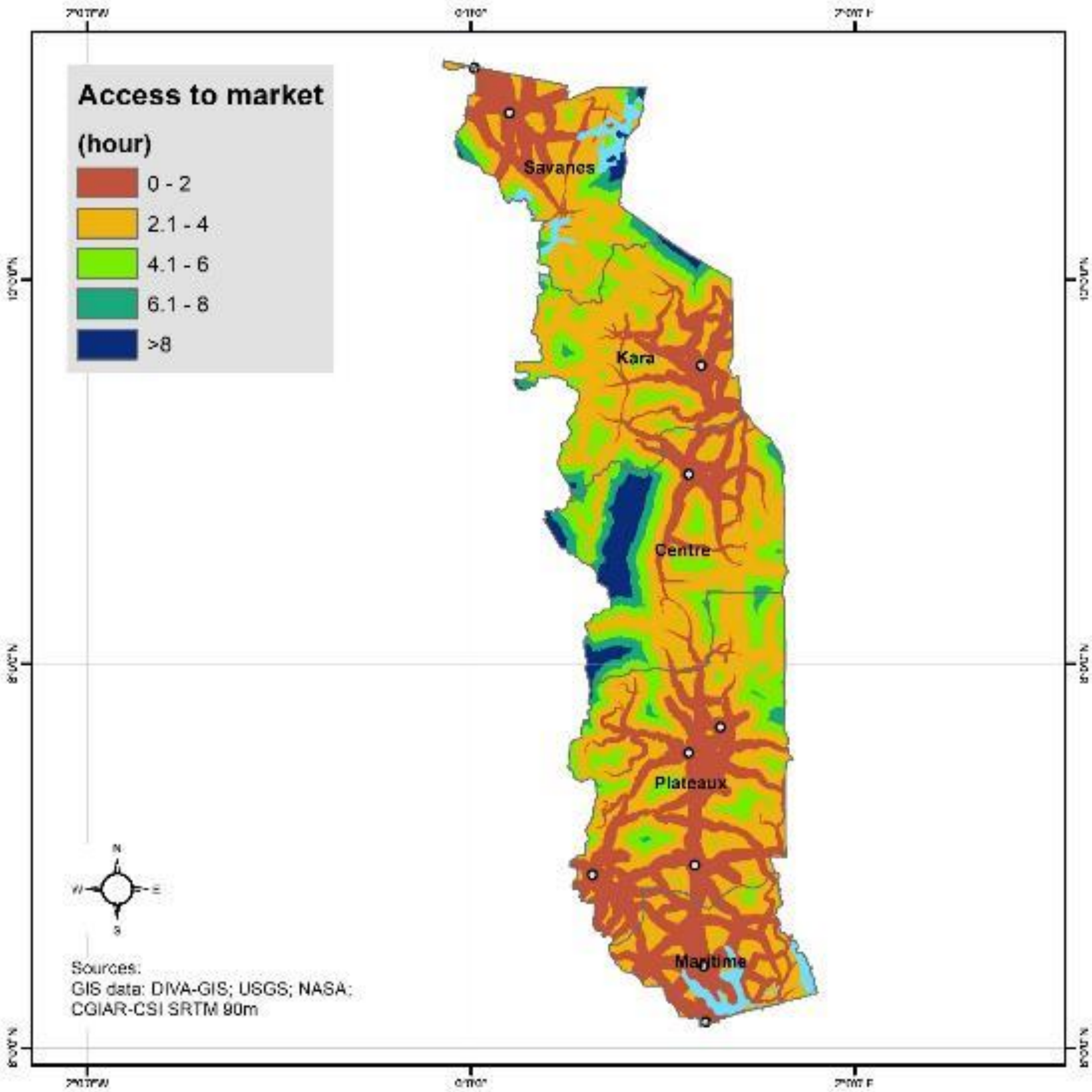

Figure 64: Togo: Accessibility

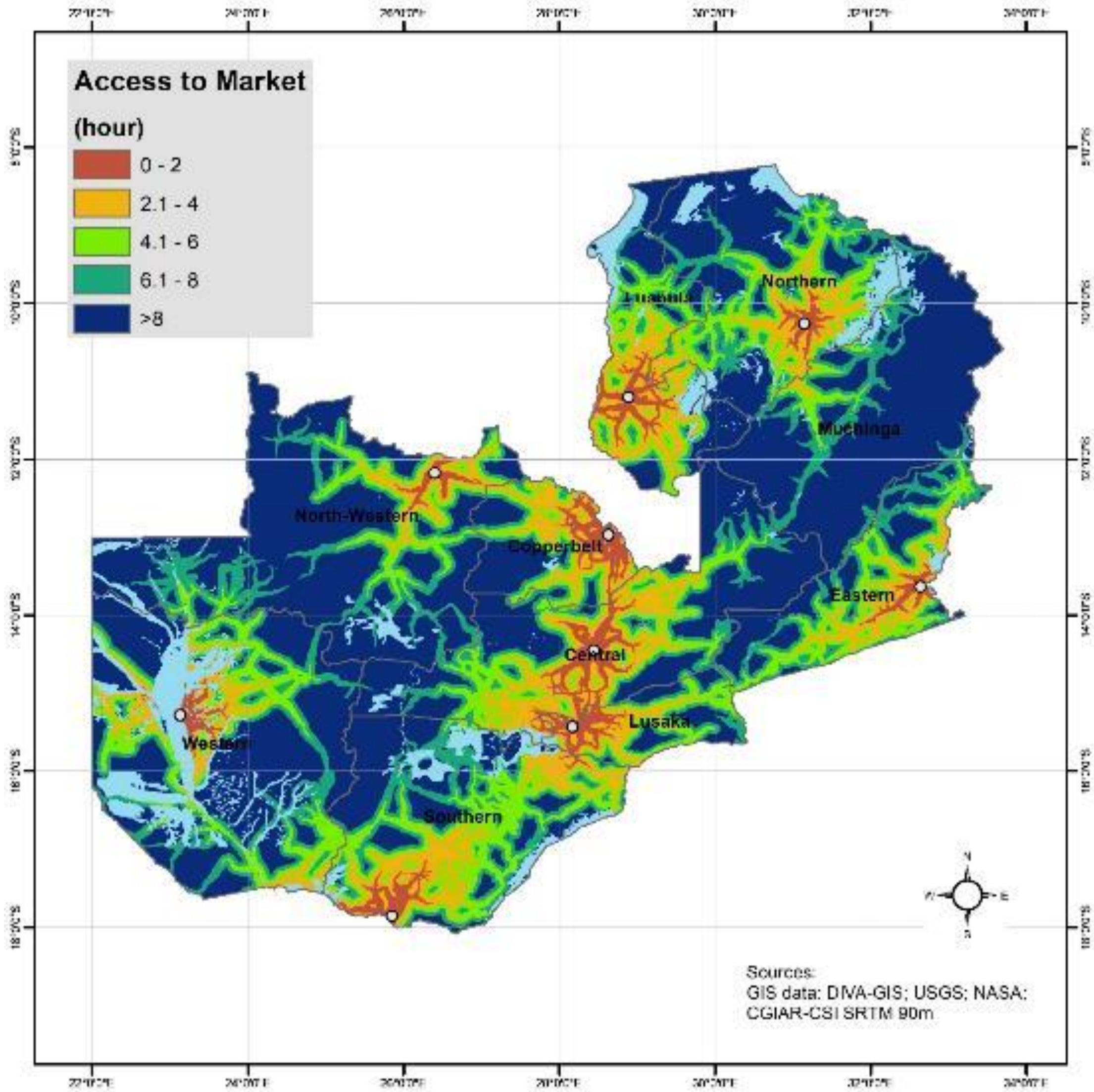

Figure 65: Zambia: Accessibility