# Geographic prioritization of agricultural investments

**IFPRI – MCC Series: Prioritizing Agricultural Investments for Income, Poverty Reduction, and Nutrition**

Technical Paper 5


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# ACRONYMS AND ABBREVIATIONS

| | |
|---|---|
| AEZ | agroecological zone |
| DEA | data envelopment analysis |
| EA | enumeration area |
| ESS3 | 2015/2016 Ethiopia Socioeconomic Survey |
| GIS | geographic information system |
| IFPRI | International Food Policy Research Institute |
| IHS | Integrated Household Survey |
| MCC | Millennium Challenge Corporation |
| SFA | stochastic frontier analysis |

# EXECUTIVE SUMMARY

Through the Notification of Funding Opportunity (NOFO) for the project "Advisory Services – Program Management for Development and Implementation within the Agricultural Sector" (DCO-PR-18-0293) issued a to the International Food Policy Research Institute (IFPRI), the Millennium Challenge Corporation (MCC) described a series of information needs and how IFPRI could provide research and analysis that would help the MCC maximize the effectiveness of their agricultural interventions. This report focuses on how agricultural investment should be prioritized across territories within countries to maximize economic returns. With this purpose in mind, we develop a spatial and economic tool for strategic analysis and visioning to help understand where the best opportunities for investments in agriculture, with specific examples for investments in irrigation and roads in Ethiopia and Malawi. For such investments to be effective for poverty alleviation, it is necessary that they lead to farm-level increases in productivity and are translated into higher incomes and better livelihoods for rural households.

Our proposed approach utilizes stochastic frontier analysis (SFA) to estimate smallholders' agricultural potential under optimal conditions and compare it with their current performance to assess their efficiency levels. SFA allows the econometric exploration of the notion that, given fixed local agroecological and economic conditions in a region and the occurrence of random shocks that affect agricultural production, the decisions farmers and policymakers make translate into higher or lower production and profits. Inefficiency is then defined as the loss incurred by operating away from an ideal production frontier, and by estimating where this frontier lies, and how far each producer is from it, SFA helps to identify local potential and efficiency levels to construct the typology. For this report, we show how this approach can allow us to compare estimated agricultural potential and efficiency levels under current conditions and hypothetical investment scenarios and calculate what are the agricultural profit gains linked to each case. We can then extrapolate these results at the regional level for the whole country and combine them with GIS data on local agroecological conditions, water availability, topography, and road infrastructure to construct our typology. In particular, we use our typology results to assess where investments in agriculture would be more effective in bringing rural households out of poverty (closing the poverty gap), and how two different types of investments can increase rural households' incomes through an increase in the profitability of smallholder agriculture. The first scenario looks at the impact of an increase in access to irrigation through river diversion methods, while the second scenario looks at the impact of an increase in market access, which we simulate by analyzing what would be the impact of reducing travel time to the nearest market (city of least 25,000 inhabitants) from any farm in the country by 50%.

For Ethiopia, we find pockets of considerable unattained farm profits located throughout the central and western parts of the country, where opportunities for investments to close efficiency gaps in agricultural production and marketing can yield high returns. Low potential in the eastern lowlands limit opportunities for gains from efficiency-oriented investments, and development efforts in these regions should be focused in long-term, large scale interventions that shift the agricultural frontier. With respect to poverty alleviation, our results show that for many regions in the country, especially in the high central plateau, investing in increasing the efficiency of smallholders would be enough to close the poverty gap. In contrast, many areas in the Somali, Tigray, Afar, Oromia, and SNNP regions would require unrealistically high shifts in their agricultural potential due to its current low level combined in many cases with higher than average poverty gaps. The results from the improved irrigation access scenario are heavily constrained by the surface water availability constraint and show that the largest impacts would be observed in Somali and Afar, while in the case of the improved market access scenario, these benefits would extend to Tigray as well.

For Malawi, our maps show higher agricultural potential in the Northern and Central regions of the country, consistent with 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). The southern region suffers from lower potential due to poorer general weather conditions and lower rainfall levels. The unattained potential map shows that despite 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 investments in those areas as well. The poverty analysis shows that the incidence and depth of poverty are higher in the Southern Region of Malawi, but that the poverty gap in all districts of the country could be closed by investing in efficiency enhancing interventions in agriculture without depending on investments that shift the agricultural profit frontier. The results from the improved irrigation access scenario show a larger impact in the Central Region of the country, particularly the districts of Kasungu, Dowa, and Salima, while the improved market access scenario benefits are more evenly spread out across the country.

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# 1 INTRODUCTION

Through the Notification of Funding Opportunity (NOFO) for the project "Advisory Services – Program Management for Development and Implementation within the Agricultural Sector" (DCO-PR-18-0293) issued a to the International Food Policy Research Institute (IFPRI), the Millennium Challenge Corporation (MCC) described a series of information needs and how IFPRI could provide research and analysis that would help the MCC maximize the effectiveness of their agricultural interventions. Based on a series of discussions with IFPRI, MCC expressed interest in three tasks: (1) Task A is to develop evidence-based strategies for incorporating nutrition-sensitive programming in multiple countries; (2) Task B is to provide analysis and recommendations addressing governing policies that affect private sector investment, adoption of improved technologies, efficiency of food systems, and employment within the agricultural sector in multiple countries; and (3) Task C is to evaluate economic-based decision mechanisms for agricultural and nutrition-sensitive investment in multiple countries.

The agricultural component of Task C involves five related steps, each of which builds on the previous ones. The first step reviews existing research on the contribution of agricultural investments to broader economic growth and poverty reduction. The second step is to develop tools and methods for incorporating these effects into the constraint analysis carried out by the MCC in compact countries. Steps 3-5 involve an assessment of methods for prioritizing different types of agricultural investments based on cross-country analyses and information on target countries. These steps would include methods for prioritizing types of investments across countries, agricultural commodity value chains, and agricultural zones or territories within countries. This report focuses on the latter, i.e., how should agricultural investment be prioritized across territories within countries to maximize economic returns. With this purpose in mind, we develop a spatial and economic tool for strategic analysis and visioning to help understand where the best opportunities for investments in agriculture, with specific examples for investments in irrigation and roads in Ethiopia and Malawi. For such investments to be effective for poverty alleviation, it is necessary that they lead to farm-level increases in productivity and are translated into higher incomes and better livelihoods for rural households.

Our proposed approach utilizes stochastic frontier analysis (SFA) to estimate smallholders' agricultural potential under optimal conditions and compare it with their current performance to assess their efficiency levels. SFA allows the econometric exploration of the notion that, given fixed local agroecological and economic conditions in a region and the occurrence of random shocks that affect agricultural production, the decisions farmers and policymakers make translate into higher or lower production and profits. Inefficiency is then defined as the loss incurred by operating away from an ideal production frontier, and by estimating where this frontier lies, and how far each producer is from it, SFA helps to identify local potential and efficiency levels to construct the typology. For this report, we show how this approach can allow us to compare estimated agricultural potential and efficiency levels under current conditions and hypothetical investment scenarios (improved access to irrigation and markets) and calculate what are the agricultural profit gains linked to each case. We can then extrapolate these results at the regional level for the whole country and combine them with GIS data on local agroecological conditions, water availability, topography, and road infrastructure to construct our typology. Our analytical results and typology maps for Ethiopia and Malawi highlight the spatial heterogeneity in opportunities and priorities for productive investments in agriculture in both countries.

The rest of this document is organized as follows. Section 2 describes the methodological approach including the conceptual framework, the SFA model, the empirical strategy, and data sources. Sections

3 and 4 present the results for Ethiopia and Malawi, respectively, which include an illustration of the spatial heterogeneity in key factors affecting smallholder agriculture, the SFA estimation results, and the maps for agricultural potential and efficiency, poverty, and investments in irrigation and market accessibility. Section 5 presents the main conclusions from the study.

# 2 METHODOLOGICAL APPROACH

## 2.1 Conceptual framework

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 investments in rural development by identifying the spatial heterogeneity in the conditions for, and the performance of, agricultural activities in any region of the world. In most sub-Saharan African countries' typologies have been a popular instrument to design rural development polices but have focused mainly on a straightforward characterization of types of farms or households, based on different criteria such as their endowment of production factors, consumption needs, and income levels.

However, understanding the biophysical and economic dimensions of the environment in which agriculture takes place to help prioritize infrastructure investments such as irrigation and roads requires an approach that combines economic, statistical, and spatial analysis tools to identify not only smallholders' current agricultural performance, but also their true potential and the factors keeping them from attaining it. Most studies looking to prioritize irrigation investments, for example, focus mainly on the availability of water resources and constraints around cultivable land, without adequate consideration of the agricultural potential of a region and the local market characteristics. Likewise, most efforts to guide investments in road infrastructure expansion have been based on population density as the main criteria for prioritization, ignoring any measures of local agricultural or economic performance.[2] This type of approaches fail to offer an adequate prioritization criterion when resources for infrastructure investments are limited and there is an urgent need for short- and medium-term results that can be reflected in significant economic growth and poverty reduction. In that sense, it is necessary to construct a typology that helps to maximize the social and private returns of infrastructure investments such as irrigation and roads by identifying areas with high potential for agricultural and economic development.

Our proposed approach, explained in more detail in the next sections, utilizes stochastic frontier analysis (SFA) to estimate average household gains in agricultural potential and efficiency by comparing smallholders' performance under current conditions and under separate scenarios of improved access to irrigation and markets. To assess the impact of investments in irrigation and roads, we assume that this type of infrastructure investments expands smallholders' profit frontiers, which has an immediate effect on their realized profits even when holding their efficiency levels constant. We then calculate what would be the additional gain from the higher profit frontier values once efficiency levels rise. For the case of irrigation, we also include in the frontier specification GIS information on water availability and topography (slope) to account for access to water sources for irrigation.

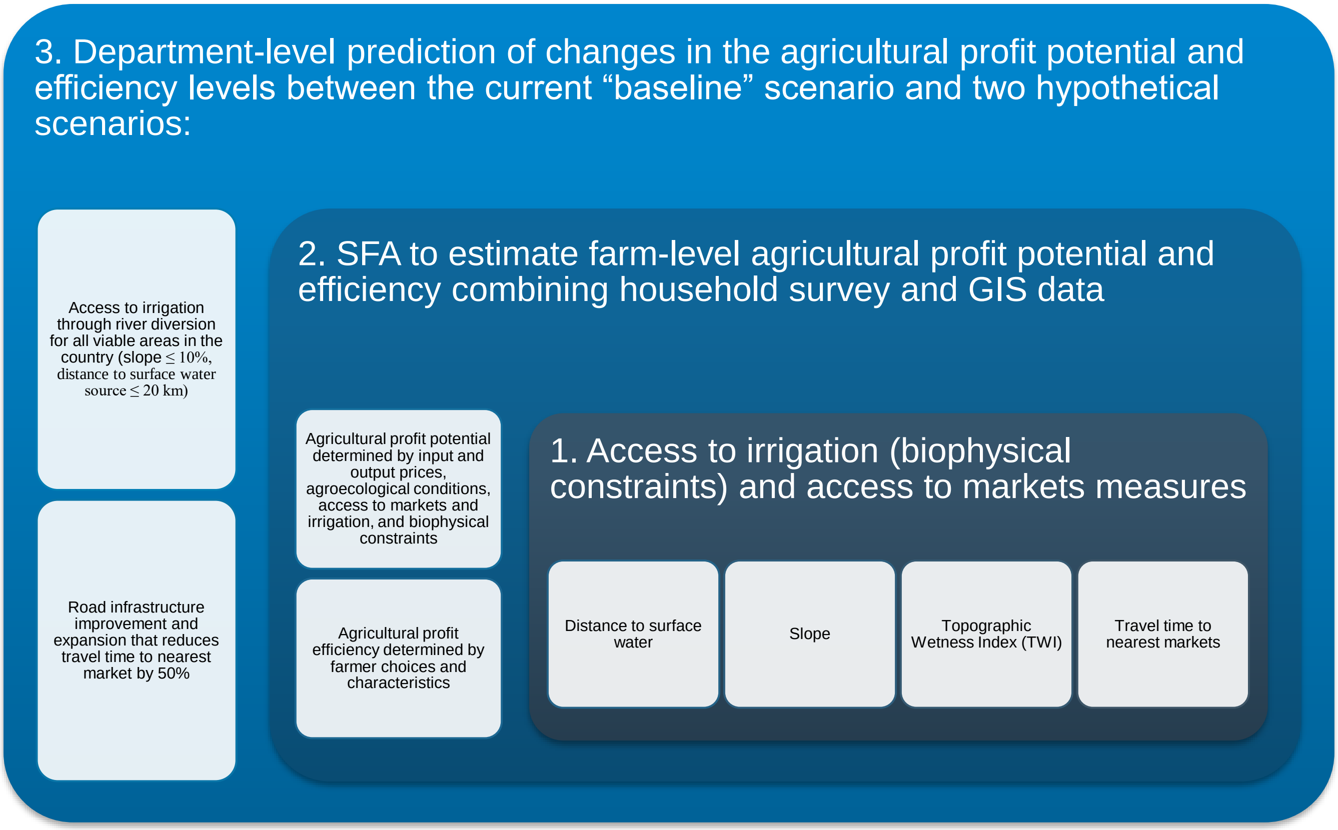
[1] See also Bigman and Fofack (2000) for a comprehensive review of GIS applications for targeting poverty alleviation programs.

[2] See for instance, the modeling exercises developed by Mentis, et al. (2015) for Nigeria, or Parshall, et al. (2009) for Kenya

The methodology for our analysis is illustrated in **Error! Reference source not found.**. SFA allows us to estimate jointly the agricultural profit potential and efficiency levels for the farmers in our sample. Intuitively, the variables used to model profit potential are those that measure the factors affecting the environment in which the smallholder operates, but which are generally beyond his direct control, such as input and output prices, agroecological conditions, access to markets and irrigation, and biophysical constraints. The variables used to model profit efficiency are the smallholder´s choice variables and characteristics, which he can control and modify (to a certain extent in the short run), to improve his performance. Within this framework, we consider that access to types of irrigation that require large investments, such as river diversion methods, increase smallholders' profit potential while biophysical constraints to those types of investments (such as the distance to surface water sources and extreme slopes) limit it.[3] Likewise, access to markets defined as the time required to travel from the nearest market to the farm depends on improvements and expansion of the road network beyond the direct control of the farmer, and therefore affect agricultural profit potential levels. With this setup we can then simulate scenarios of improved access to irrigation and markets and assess how they impact agricultural profit potential, and given current levels of efficiency, realized farm profits and extrapolate these results for the whole country to construct our typology.

[3] Other types of irrigation investments that can be implemented at the community or individual farmer level such as extracting ground water using treadle or motor pumps are considered to affect the farmer's efficiency level rather than his potential.

**Figure 1: Methodological approach to construct the spatial targeting tool**




## 2.2 Model

The two most commonly used methods to estimate the efficiency of production units are data envelopment analysis (DEA) (Charnes, et al., 1978; Charnes, et al., 1981) and stochastic frontier analysis (SFA) (Aigner, et al., 1977; Meeusen & van den Broeck, 1977; Battese & 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 are 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]

[4] See for example Park & Simar (1994), Kumbhakar & Tsionas (2008), and Martins-Filho & 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.

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 and production decisions 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 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 2.

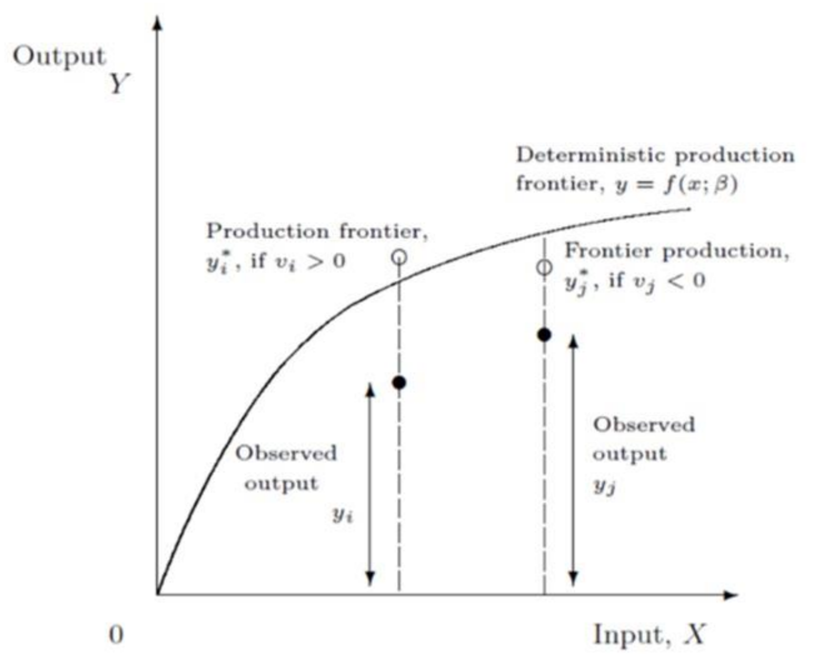



**Figure 2. Illustration of the stochastic production frontier in the single-output, single-input case**

Using the basic model proposed by Aigner, et al. (1977) and Meeusen & van den Broeck (1977) 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 $\beta$, $v_i$ 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:

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

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 for 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 $u_i$:

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

where $z_i$ are farmer-specific factors affecting his or her technical efficiency.

## 2.3 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 or revenue function approach. The stochastic frontier profit function can be expressed as (Kumbhakar & Lovell, 2000):

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

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:

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

where $AEZ$ are the agroecological zone variables.

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 data requirements are a recent household survey representative at the national and sub-national levels, that includes information on farm revenues, agricultural prices, and farm and household characteristics, as well as GIS on local agroecological characteristics, such as land use, as well as for market access measures. The household survey datasets used for this study for Ethiopia and Malawi are described in the next section.

## 2.4 Data

### *Ethiopia*

### Table 1: Malawi: IHS4 summary statistics

| | Estimation sample | Rest of ag. sample | T-test |
|---|---|---|---|

| | Mean | Std. Dev. | Mean | Std. Dev. | Difference | |
|---|---|---|---|---|---|---|
| **Household characteristics** | | | | | | |
| **Household size** | 5.35 | 2.30 | 5.26 | 2.26 | 0.09 | |
| **Head female (%)** | 0.19 | 0.39 | 0.25 | 0.44 | -0.06 | *** |
| **Maximum schooling in the household (years)** | 4.82 | 3.58 | 5.27 | 3.91 | -0.46 | *** |
| **Land ($m^2$)** | 9,739.05 | 10,976.96 | 12,111.70 | 23,459.25 | -2,372.65 | *** |
| **Own a modern plough (%)** | 0.05 | 0.22 | 0.03 | 0.18 | 0.02 | ** |
| **Agroecological, biophysical, and accessibility measures** | | | | | | |
| **Slope** | 8.87 | 4.39 | 7.67 | 4.40 | 1.21 | *** |
| **Elevation (m)** | 1,823.68 | 486.03 | 1,955.09 | 555.35 | -131.42 | *** |
| **Annual precipitation (mm)** | 1,159.27 | 370.94 | 1,118.43 | 390.99 | 40.84 | *** |
| **Topographic wetness index** | 12.29 | 1.56 | 12.58 | 1.81 | -0.29 | *** |
| **Nutrient retention capacity constraint** | 1.29 | 0.48 | 1.28 | 0.67 | 0.00 | |
| **Time to market (hours)** | 3.61 | 7.85 | 3.25 | 5.95 | 0.36 | |
| **Irrigation method (%)** | | | | | | |
| **River diversion** | 0.09 | 0.29 | 0.03 | 0.17 | 0.06 | *** |
| **Motorized pump** | 0.03 | 0.16 | 0.01 | 0.12 | 0.01 | ** |
| **Manual** | 0.01 | 0.11 | 0.02 | 0.14 | -0.01 | |
| **Other** | 0.01 | 0.12 | 0.03 | 0.17 | -0.01 | *** |
| **Observations** | | 1216 | | 1839 | | |

The 2015/2016 Ethiopia Socioeconomic survey (ESS3) is the third wave of the survey and forms a panel with the previous two waves. While ESS3 includes both urban and rural households, the first wave of the survey (ESS1) was only representative of rural areas. The initial rural sample was selected using a two-stage stratified sampling strategy where regions were used as the strata to select EAs. The urban sample was added during the ESS2 and used a two-stage stratified sampling procedure. Of the initial 3,969 rural households interviewed in ESS1, 3,699 were revisited during ESS3. These, along with the addition of 1,255 urban households, results in a sample size of 4,954. The sample is representative nationally and of urban and rural areas, as well as across five regional domains: Amhara, Oromiya, SNNP, Tigray, and all other regions. The ESS3 was conducted from September 2015 to April 2016. Questionnaires were administered during post-planting and post-harvest interviews for rural households and in one visit for urban households. To conduct the frontier estimation, we restrict the sample to include only the 1,216 households that have positive crop profits (out of 3,055 that reported planting at least one crop). Summary statistics on household characteristics, agroecological, biophysical, and accessibility measures, and irrigation methods for the estimation sample and the remaining 1,839 agricultural households are shown in **Error! Reference source not found.** (summary statistics for input and output prices can be found in **Error! Reference source not found.** in the appendix). While there are several statistically significant differences between the two samples, most of these differences are small in magnitude.

### *Malawi*

## Table 2: Malawi: IHS4 summary statistics

| | Estimation sample | | Rest of ag. sample | | T-test | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev | Mean | Std. Dev | Difference | |
| **Household characteristics** | | | | | | |
| **Farm assets (MWK)** | 17,758.50 | 66,434.13 | 14,284.16 | 127,275.02 | 3,474.35 | |
| **Land (m²)** | 8,179.49 | 6,774.89 | 5,779.04 | 4,940.41 | 2,400.46 | *** |
| **Household size** | 4.51 | 1.95 | 4.46 | 2.01 | 0.04 | |
| **Maximum education in the household (years)** | 7.56 | 3.10 | 7.44 | 3.46 | 0.12 | * |
| **Female head (%)** | 0.26 | 0.44 | 0.32 | 0.47 | -0.07 | *** |
| **Agroecological, biophysical, and accessibility measures** | | | | | | |
| **Slope** | 2.30 | 1.74 | 2.38 | 1.72 | -0.08 | ** |
| **Annual precipitation (mm)** | 1,088.84 | 265.41 | 1,107.84 | 253.39 | -19.01 | *** |
| **Topographic Wetness Index** | 13.50 | 2.69 | 13.59 | 2.84 | -0.09 | |
| **Elevation (m)** | 900.09 | 335.77 | 804.96 | 350.12 | 95.13 | *** |
| **Nutrient retention capacity constraint** | 1.63 | 1.27 | 1.53 | 1.22 | 0.10 | *** |
| **Time to market (hours)** | 5.03 | 4.09 | 4.74 | 4.05 | 0.29 | *** |
| **Irrigation method** | | | | | | |
| **Stream diversion** | 0.02 | 0.12 | 0.00 | 0.07 | 0.01 | *** |
| **Other** | 0.10 | 0.30 | 0.05 | 0.23 | 0.04 | *** |
| **Observations** | | 3,264 | | 6,431 | | |

The fourth Malawi Integrated Household Survey (IHS4) was conducted between April 2016 and April 2017. While there is a panel component to the IHS surveys, the cross-sectional sample was used for our analysis. The sample was selected using a two-stage stratified design where the strata consisted of the 32 districts in Malawi. In the first stage 779 enumeration areas (EA) were selected and in the second 16 household were chosen from each EA. The resulting sample is representative at the national, district, and urban and rural levels.[6] To conduct the frontier analysis, we restricted to households that had positive crop profits, resulting in 3,297 households included in the estimation. Summary statistics for the estimation sample and the remaining agricultural households in the survey are shown in **Error! Reference source not found.**.

## 2.5 Practical considerations

To illustrate how this methodology can be applied to prioritize investments and resources for rural development, we conduct the analysis for Ethiopia and Malawi using publicly available household survey data

[6] While data was collected for the island district of Likoma, which makes up 0.1 percent of the population of Malawi, it was excluded from our analysis due to the small sample size.

and GIS information, and perform some basic projections of investment scenarios in irrigation and road infrastructure for both countries. Because of the scope of this study (which does not include data collection), our results are restricted by the assumptions needed to be made to overcome some of the specific limitations of the publicly available data. While this does not prevent our analysis from showing the heterogeneity in spatial patterns of agricultural, economic, and geographic variables that will guide investment decisions, certain considerations listed below should be taken into account when interpreting the results in Section 3.

### *Sample selection*

As mentioned in Section 2.4, we do not include in the SFA estimation sample those smallholders that did not report any output sales or who obtained less revenue from sales than what they spent on inputs. The main reason behind this choice is to obtain coefficient estimates for a function that positions profitable smallholder farms at the frontier, while acknowledging the fact that production decisions of subsistence farmers may reflect a different set of technologies and optimization criteria.

While we do not use non-profitable farms to estimate the frontier function, we do bring them back into the sample to characterize an area and predict regional estimates of agricultural potential and efficiency, so that these predicted values. In other words, while we assume the data from non-profitable farms is not informative enough or might be too noisy to pin down the profit frontier, we recognize these units represent a significant share of rural households and the contrast between their potential and their current performance given their low efficiency levels should be reflected in our regional estimates and depicted in our maps to adequately inform development-oriented investment decisions.

An advantage of making the decision of excluding farmers with non-positive profits is that we avoid the methodological challenges encountered when using a logarithmic specification of the stochastic frontier function. Common solutions to this issue have been to truncate the distribution of profits at a small positive value close to 0 or 1 or add a constant the size of the largest negative value of the profit variable to all observations in the sample. While these monotonic transformations allow for the logarithmic specifications to be used with non-positive values of the dependent variable, they can distort and muddle the relationship between profits, prices and other variables. Truncating the distribution equalizes a farm that broke even, with one that had a small loss, with one that had a huge loss, and also clusters a lot of observations at a single point causing additional problems that reduce the ability of the estimation to properly pin down the frontier. Adding a constant, especially if there are observations with large losses, [7] can also drown all the information coming from the positive side of the distribution of profits, which is the side that would be more informative for identifying the frontier. Finally, these monotonic transformations can alter the relative distance between observations, and it is hard to assess what is the impact of that on our results.

### *Frontier shifters and environmental variables*

While input and output prices are expected factors in a profit function estimation, we also include in our analysis other factors affecting the deterministic portion of the profit frontier (frontier shifters) and the variance of the technical efficiency error term (environmental variables). The frontier shifters capture the effect of factors over which the producer typically has no direct control, are fixed in the short term, or

[7] Large negative values in the profit variable can be caused by measurement error in the survey data. Incorrect entries for decimal points, or mistakes in identifying the unit or weight conversion factors for inputs used by the farm, for example, could explain large negative extreme values. More importantly, in many cases negative profits are being driven by inflated self-valuation of costs reported in the survey, or by the lack of information on how to properly assign costs to different farm activities or seasons.

cannot be easily priced, that influence the deterministic portion of the profit frontier function. In other words, these factors are external to the smallholder's decision-making process, are usually spatially clustered, and play a significant role in determining his farm profit potential. We consider in this category variables such as agroecological and biophysical conditions and measures of access to markets.

Environmental variables do not determine farm profit potential but affect profits through their impact on the smallholder's ability to operate efficiently. Unlike frontier shifters, environmental variables are a direct result of present and past decisions made by the farmer and can vary greatly from farm to farm even within a small area. Very often these environmental variables capture inefficiencies in the production process that result from market failures faced by smallholders in developing countries, such as low levels of investment due to poor access to credit or suboptimal production choices due to lack of adequate insurance products.

### *Interpretation of results from the irrigation and market access investment scenarios*

As further explained in sections 3.5 and 3.6, we use our typology results to assess how investments in irrigation and road infrastructure can increase rural households' incomes through an increase in the profitability of smallholder agriculture. The first scenario looks at the impact of an increase in access to irrigation through river diversion methods. The SFA approach allows us to estimate what would be the increase in the profit frontier associated to having access to irrigation through river diversion by *switching on* this indicator variable for observations that currently do not have access to it and satisfy certain hydrological conditions. The second scenario looks at the impact of an increase in market access, which we simulate by analyzing what would be the impact of reducing travel time to the nearest market by 50%.

Our approach assumes farmers are optimizing a profit function and embedded in it is a measure of farm output. We have chosen to introduce irrigation and market access as shifters in the profit function, meaning that improvements in these factors shift the profit frontier outwards (increase potential farm profits) for any given set of input and output prices and agroecological conditions. Once the profit frontier shifts in our hypothetical scenarios as a result of improvements in irrigation and road infrastrcucture a new optimal production plan for each farm is obtained (i.e., how much of each input to use and how much of each crop to produce), as this is the choice variable in the model's optimization problem.

Given we are only using publicly available cross-sectional secondary data for these scenarios, there are some limitations to the results we obtain and their interpretation. In the case of the market access scenario, it should be noted that the proposed intervention (reducing the travel time from any point in the country to the nearest market by 50%) might not be meaningful for extremely isolated areas, for which half the travel time might still be too high to make a big difference in the profitability of local farmers if agroecological conditions are not favorable enough or their efficiency level is too low. Intuitively, we can think of investments that reduce travel time by 50% as projects that maintain primary roads and upgrade secondary and tertiary roads, rather than major expansions of the road network through the construction of primary roads into remote unconnected regions of the country. For the latter, our analysis of

Another caveat to the market access investment scenario is that this exercise only considers as nearest markets cities (of at least 25,000 inhabitants) within the country of analysis, so access times for farms whose true nearest market is a city in a neighboring country will be higher than what they should be. However, it should be noted that market access costs for a given area in our analysis are mainly driven by the presence or absence of nearby roads rather than by the proximity to the market itself, with most of the travel time from isolated areas being taken up by the time it takes to get to the nearest road, rather than the time it takes to travel to the nearest market once on that road.

In the case of the irrigation investment scenario, we formulate the SFA estimation to construct the typology and simulate the irrigation investment exercise differencing two types of irrigation investments, the investments that can be implemented by farmers at the local or community level, and the investments that require external intervention given their larger scale and higher costs. We then assume the former affect the farmers' efficiency (how far they from the frontier) and the latter the position of the frontier itself. Finally, we add additional hydrological constraints (distance to water source and slope) before simulating the increased access to irrigation for local smallholders, to account for spatial patterns in the availability of water resources.

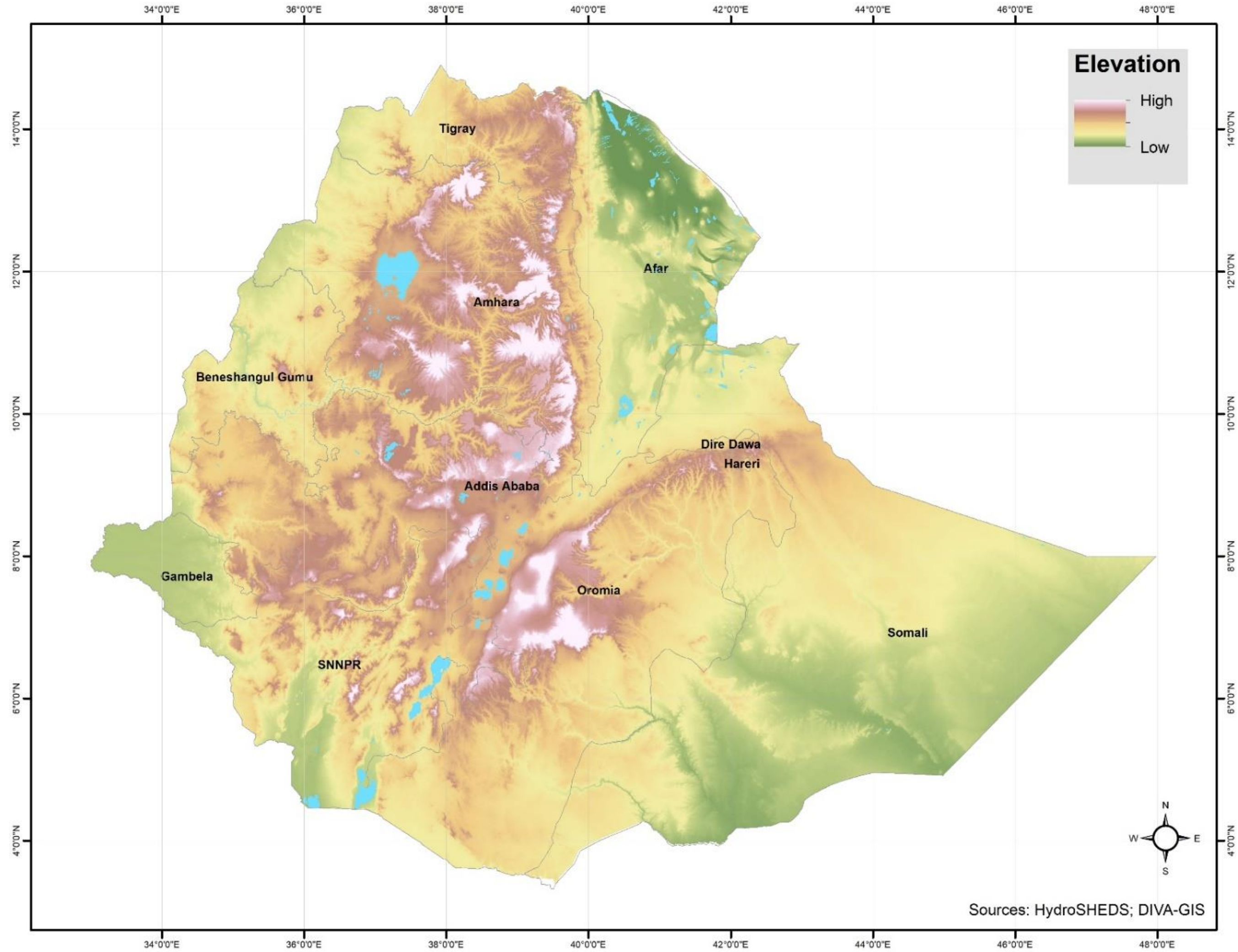
# 3 RESULTS FOR ETHIOPIA

## 3.1 Spatial heterogeneity

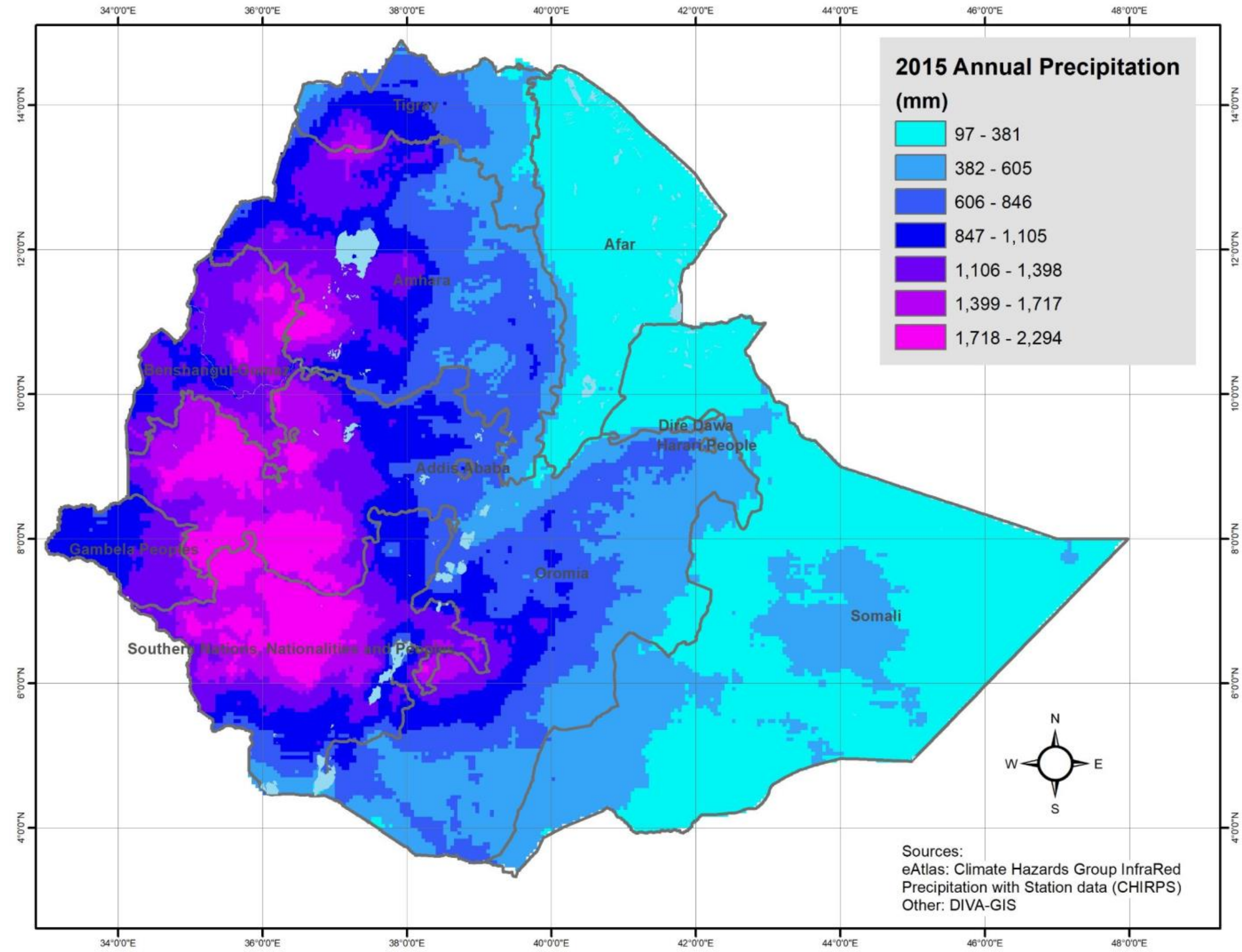
The heterogeneity in the spatial distributions of the factors affecting smallholder agriculture explain the clustering of constraints and opportunities that need to be considered when targeting agricultural investments. Before we move on to the maps showing our analytical results, it is important to illustrate this heterogeneity to better understand the geographic context in which agriculture takes place in Ethiopia.

**Error! Reference source not found.** shows the elevation map for Ethiopia. The country's geography is characterized by a high central plateau, with mountains running from north to south separated by the Rift Valley running southwest to northeast. The plateau gradually slopes to the lowlands of the Sudan on the west and the Somali plains in the east. Elevation is also closely linked with rainfall patterns (**Error! Reference source not found.**), which, in a context where most smallholder production depends on rainfed agriculture, are extremely important. The map shows a clear east-west divide, with higher elevations receiving substantially more precipitation than lowlands.

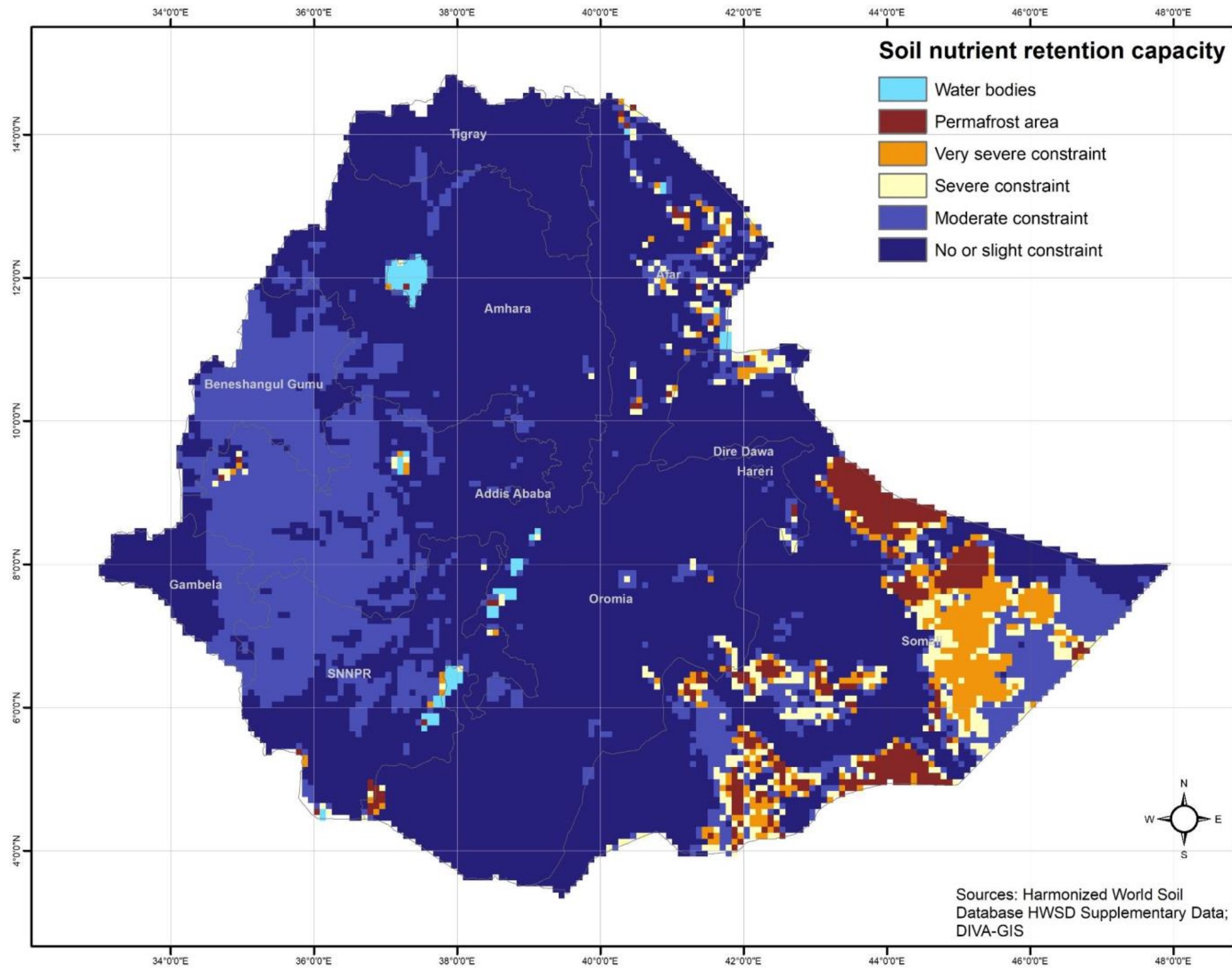
## Figure 3: Ethiopia: Elevation



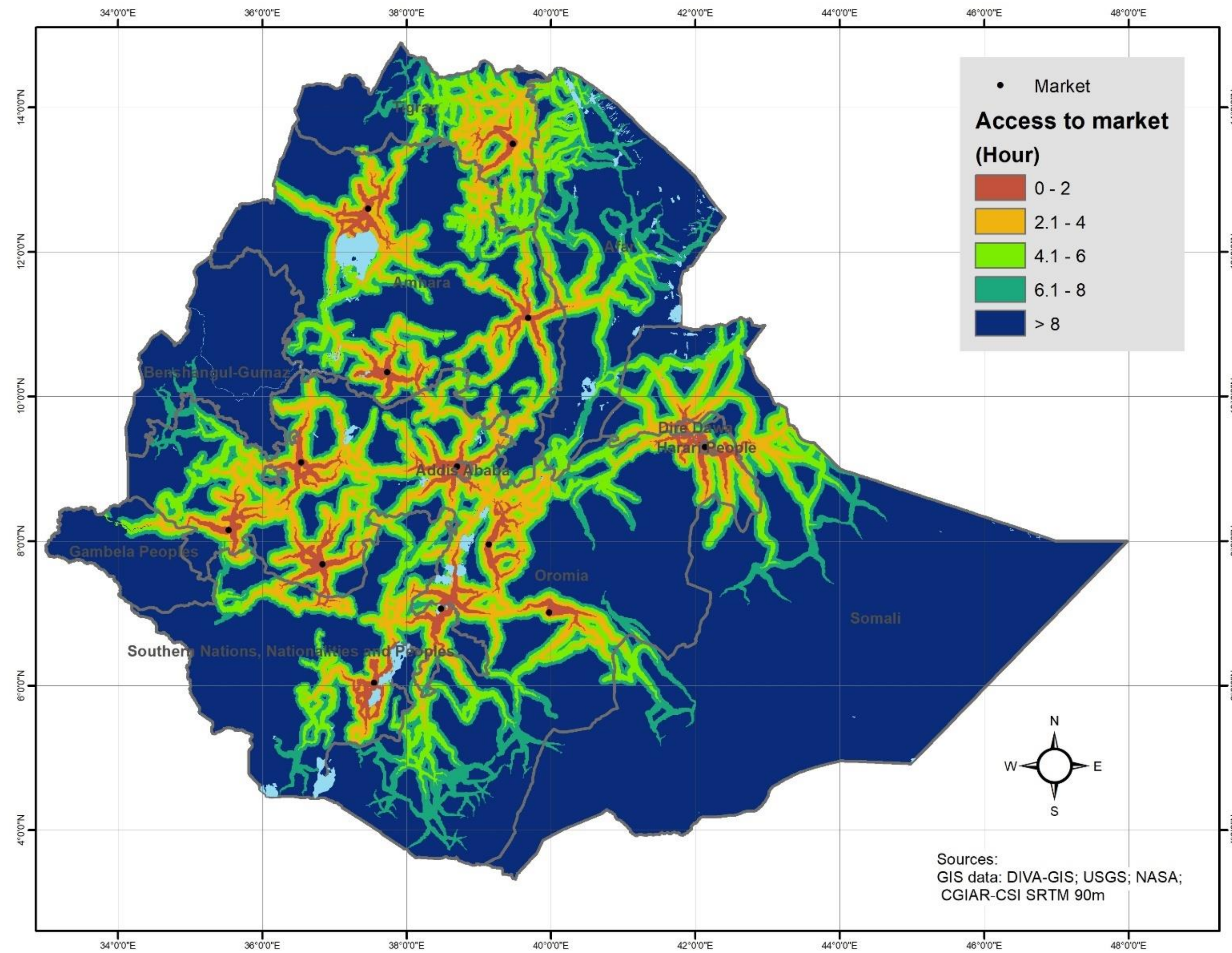
## Figure 4: Ethiopia: Annual precipitation (2015)



## Figure 5: Ethiopia: Soil nutrient retention capacity



## Figure 6: Ethiopia: Travel time to the nearest city of 25,000 inhabitants or more



Another key factor that explains heterogeneity in agricultural productivity is soil quality. **Error! Reference source not found.** shows the spatial distribution of the soil nutrient retention capacity indicator, that measures the capacity of the soil to retain added nutrients against losses caused by leaching. It shows that soil quality is poorer in the East of the country, particularly in the Somali region. However, it should be noted that recent studies indicate that soil quality is also declining in the central and northern highlands of Ethiopia under current high cultivation intensity practices of cereal based cropping systems that are pushing soils towards exhaustion and productivity loss.

Beyond the biophysical conditions under which smallholders operate and which determine their productive capacity, their profitability greatly depends on their outputs reaching distant markets at a reasonable cost. **Error! Reference source not found.** illustrates the different levels of market accessibility across Ethiopia, as measured by the required travel time from any point in the country to the nearest city of 25,000 inhabitants or more. This is calculated by splitting the country in small cells, and then estimating how much time it would take to travel through each of those cells. Cells containing a road, evidently, can be traveled through much faster than those without one, and the type of road also matters (traveling through a paved road is faster than a dirt road). Then, to travel from point A to point B in the map an algorithm picks the fastest route comprised of a chain of cells with the lowest possible total travel time. **Error! Reference source not found.** shows that, although the road network has expanded considerably in the last 30 years in Ethiopia, the lowlands are still considerably disconnected from major cities and markets with travel times higher than 8 hours.

The spatial heterogeneity in the distributions of different biophysical and economic factors that affect agricultural production and marketing translate to a high variation of farmgate prices for different crops across the country. Figures **Error! Reference source not found.** and **Error! Reference source not found.** show the farmgate prices for teff and khat in different regions of the country, with higher prices being observed in dark colored regions. As shown in the maps, there is no one single national price for each crop, nor there is a strong correlation in spatial price patterns of the two crops. Underlying our estimates of agricultural profit potential and efficiency that are the main building blocks for our proposed typology is this high spatial heterogeneity in biophysical and economic conditions in which smallholders operate.

## 3.2 SFA estimation results

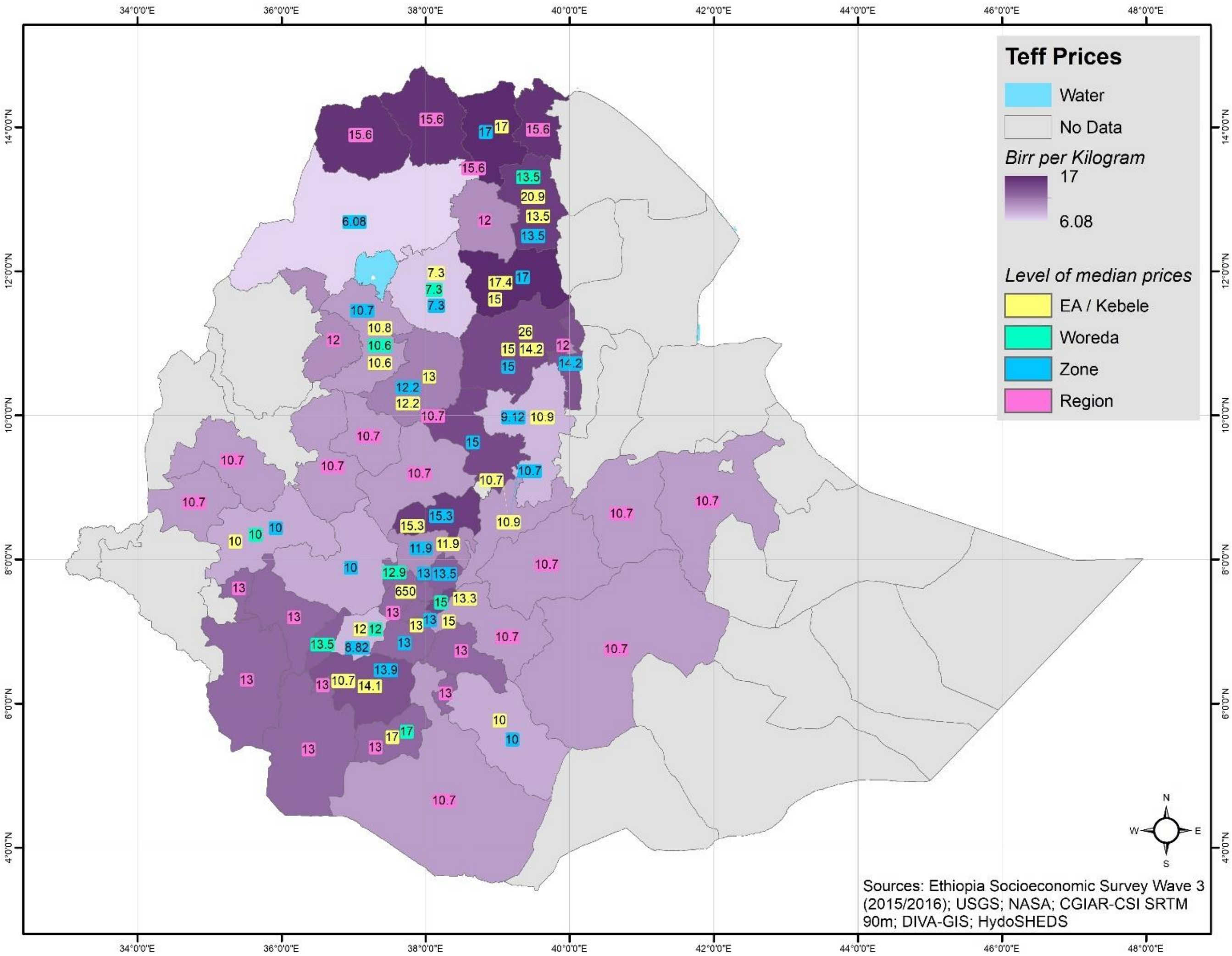
Table 3 shows the results of the stochastic frontier estimation for Ethiopia.[8] The deterministic portion of the agricultural profit frontier is a function of input and output prices, AEZs (land use variables), access to irrigation (through river diversion), access to markets (travel time to the nearest city of 25,000 inhabitants or more), and additional GIS variables that characterize the context in which smallholders operate. The factors influencing (the variance of) the non-negative component of the error term associated with farm efficiency are farm or community level irrigation investments, physical capital (land, farm assets), and human capital (household size, household head characteristics). The estimated coefficients from the regression in this table are used to predict regional level agricultural potential and efficiency.

Our main interest for the irrigation and accessibility scenarios we want to assess are the coefficients for irrigation (river diversion) and time to market (hours). The positive and significant sign on the irrigation variable indicates that smallholders that reported having access to irrigation through river diversion have a higher profit frontier, i.e., higher profit potential. Conversely, the negative and significant sign on the

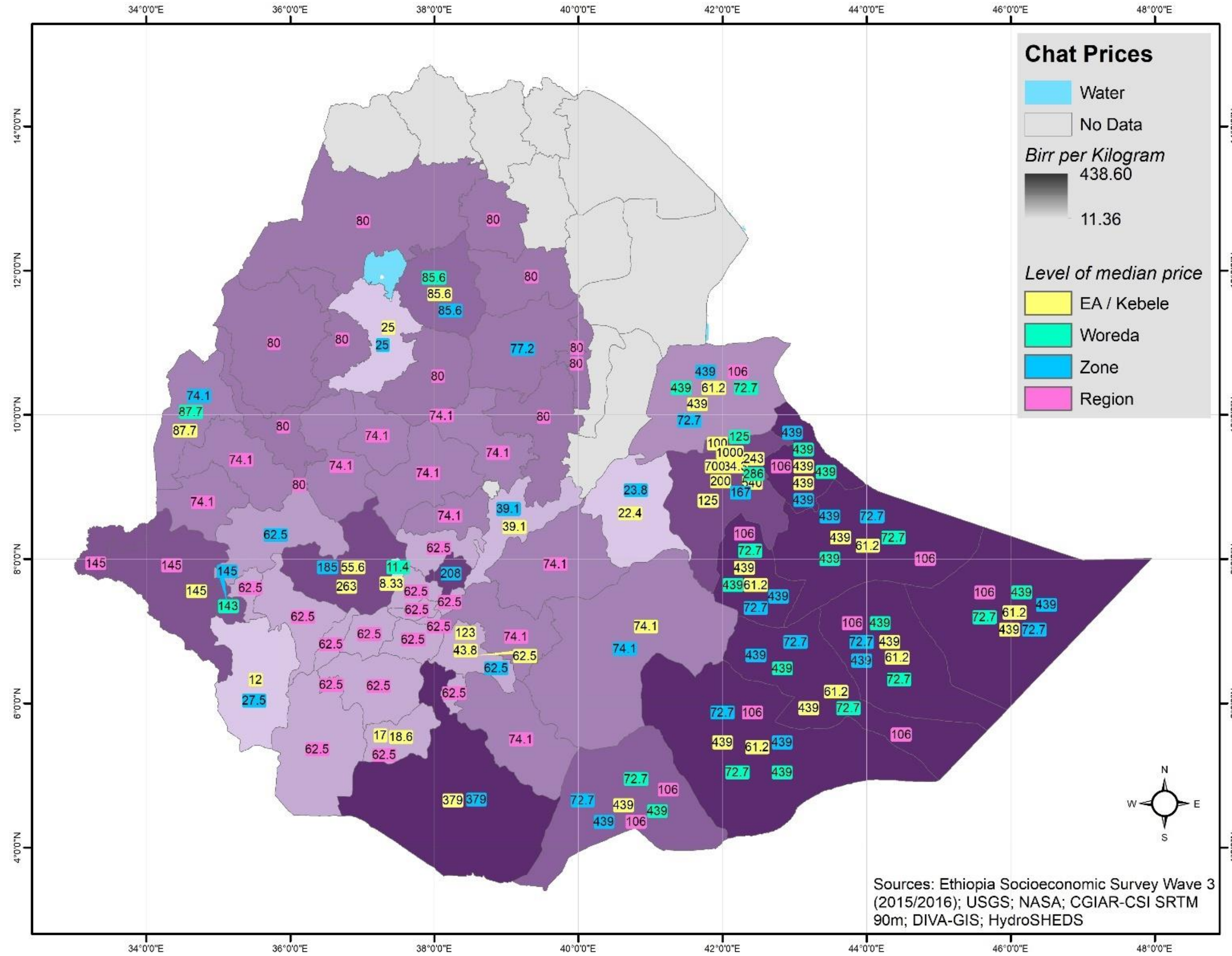
[8] All variables measured in monetary values (Birr) are normalized using the price of maize (as explained in the Estimation section).

time to market variable indicates that an increase in the distance between the farm and the nearest market is associated with a decrease in profit potential.

## Figure 7: Ethiopia: Farmgate prices for teff (Birr per kilogram)



## Figure 8: Ethiopia: Farmgate prices for khat (Birr per kilogram)

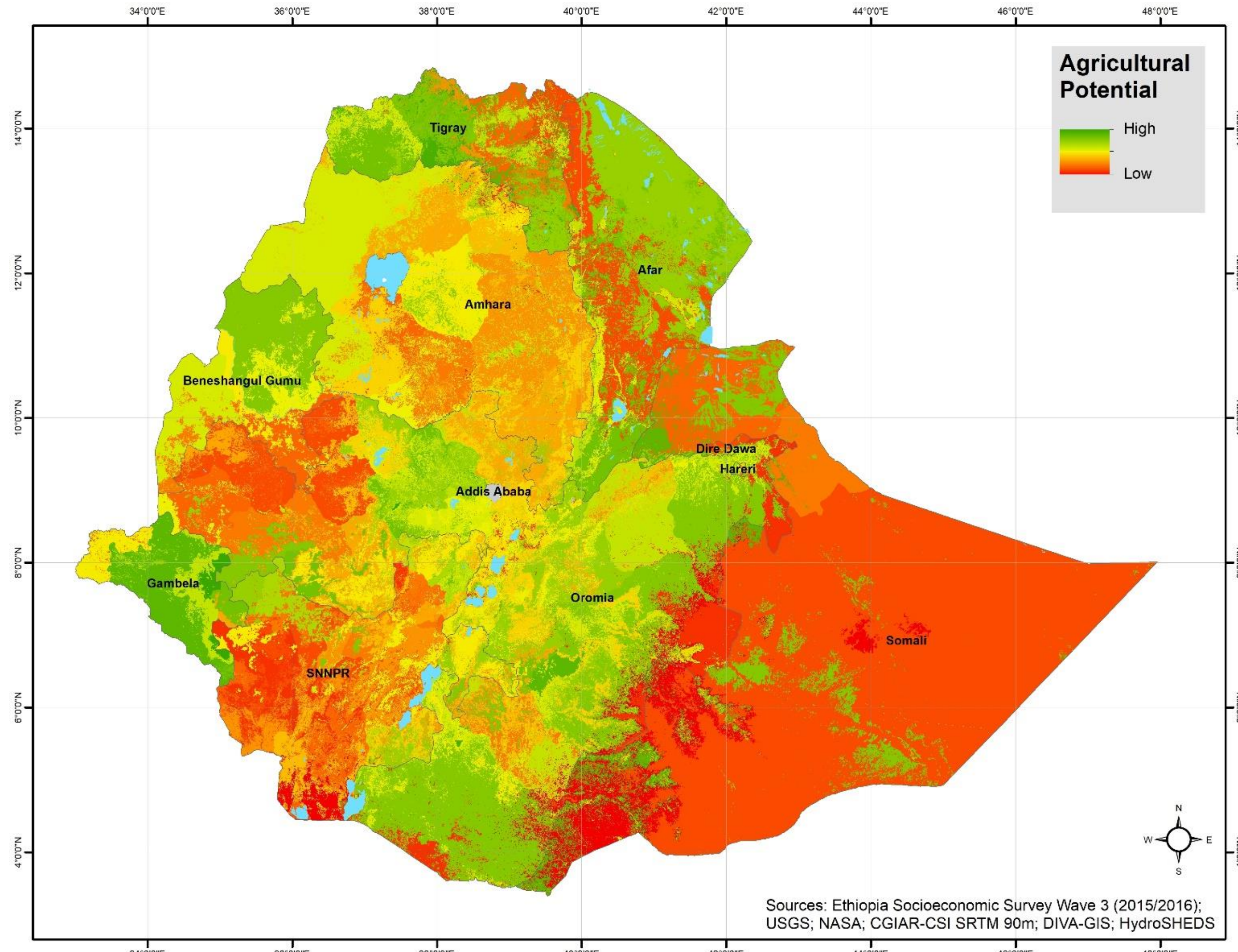


## Table 3: Ethiopia: SFA estimation

| ***ln(Crop Profits)*** | Coeff. | Std. Error |
|---|---|---|
| *Crop Prices* | | |
| Sorghum | 0.865 | 0.326*** |
| Teff | -0.270 | 0.132** |
| Wheat | 1.282 | 0.671* |
| Sesame | 1.507 | 0.475*** |
| Banana | -0.342 | 0.137** |
| Chat | 0.312 | 0.097*** |
| Coffee | -0.208 | 0.107** |
| *Seed Prices* | | |
| Improved Maize | -0.192 | 0.178 |
| Traditional Maize | -0.241 | 0.243 |
| Sorghum | 0.309 | 0.266 |
| Teff | - 0.240 | 0.546 |
| Wheat | - 0.524 | 0.424 |
| Barley | - 0.423 | 0.521 |
| Horse beans | -1.476 | 0.634** |
| *Fertilizer Prices* | | |
| Urea | 0.072 | 0.067 |
| DAP | -0.280 | 0.270 |
| NPS | -0.133 | 0.152 |
| *log Wages* | | |
| Men | 0.117 | 0.081 |
| Women | 0.614 | 0.162*** |
| Children | -0.222 | 0.169 |
| *Land Use* | | |
| Evergreen Forest | 1.811 | 0.423*** |
| Closed shrublands | -13.801 | 5.200*** |
| Open shrublands | -1.973 | 0.495*** |
| Woody savannas | -0.647 | 0.407 |
| Savannas | 0.833 | 0.316*** |
| Grasslands | 1.075 | 0.356*** |
| Croplands | -0.330 | 0.348 |
| Urban, wetlands, or barren | 0.780 | 7.024 |
| *Geographic and environmental characteristics* | | |
| Slope | 0.002 | 0.013 |
| Average precipitation | $7.0\text{x}10^{-5}$ | $2.8\text{x}10^{-4}$ |
| Topographic wetness index | 0.039 | 0.031 |
| Elevation | $3.6\text{x}10^{-4}$ | $1.6\text{x}10^{-4}$** |
| Nutrient retention capacity constraint | -0.537 | 0.121*** |
| Time to Market (hrs) | -0.020 | 0.012* |
| Irrigation: river diversion | 0.250 | 0.148* |
| Constant | 8.479 | 1.120*** |
| $\boldsymbol{ln\sigma_v}$ | | |
| Constant | -0.653 | 0.293** |
| $\boldsymbol{ln\sigma_u^2}$ | | |
| Irrigation: motorized pump | -0.469 | 0.521 |
| Irrigation: manual method | -0.595 | 0.507 |
| Irrigation: other method | -0.554 | 0.417 |
| Land ($m^2$) | $-9.5\text{x}10^{-6}$ | $-7.6\text{x}10^{-6}$ |
| Modern plough | -0.259 | 0.281 |
| Household size | 0.002 | 0.033 |
| Maximum household education (years) | -0.061 | 0.021*** |
| Female head | 0.497 | 0.175*** |
| Constant | 1.487 | 0.237*** |
| $\sigma_v$ | 0.721 | 0.106 |
| N | | 1,216 |

*Sources: Ethiopia Socioeconomic Survey Wave 3 (2015/2016); NASA; USGS; CGIAR-CSI SRTM90m; HydroSHEDS*

## Figure 9: Ethiopia: Agricultural profit potential



## 3.3 Agricultural potential and efficiency

**Error! Reference source not found.** shows the estimated agricultural potential across Ethiopia, where agricultural potential is defined as the maximum profit that a farmer can gain from crop production if operating at maximum efficiency. In general, regions in the east have lower agricultural potential, consistent with rainfall, elevation, and soil quality patterns shown previously, as well as biophysical constraints such as soil quality. The agricultural potential of a region can only be increased in the medium to long run through investments that shift the profit frontier such as R&D and technological innovations (e.g., new seed varieties, agricultural practices, production technologies, etc.) and large-scale infrastructure (irrigation, roads, electrification, ICTs, etc.).

**Error! Reference source not found.** shows the estimated smallholder agricultural efficiency, which measures how much of the potential has been attained by the average farmer in each region. Efficiency gaps can be closed through several short- and medium-term interventions that increase smallholders' productivity and will depend on what are the specific bottlenecks affecting each region. For example, a region might be extremely suitable to produce a high value horticultural crop, but farmers in that area might not have access to the capital needed to invest in the necessary equipment and seeds, or the technical assistance to grow and care for that crop. Programs that give farmers access to credit and technical assistance can be implemented relatively quickly and help close those efficiency gaps, usually much faster than what it takes to shift the profit frontier and increase their potential.

Combining the agricultural potential (**Error! Reference source not found.**) and efficiency (**Error! Reference source not found.**) estimates we can construct a measure to identify which are the regions where closing efficiency gaps would yield the highest returns. This measure is the amount of potential profit that has not been attained yet, i.e., $(1 - TE_i) \times \pi_i$, and is depicted in **Error! Reference source not found.**. Pockets of considerable unattained farm profits are located throughout central and western Ethiopia, where opportunities for investments to close efficiency gaps in agricultural production and marketing can yield high returns. Low potential in the eastern lowlands limit opportunities for gains from efficiency-oriented investments, and development efforts in these regions should be focused in long-term, large scale interventions that shift the agricultural frontier.

## 3.4 Poverty

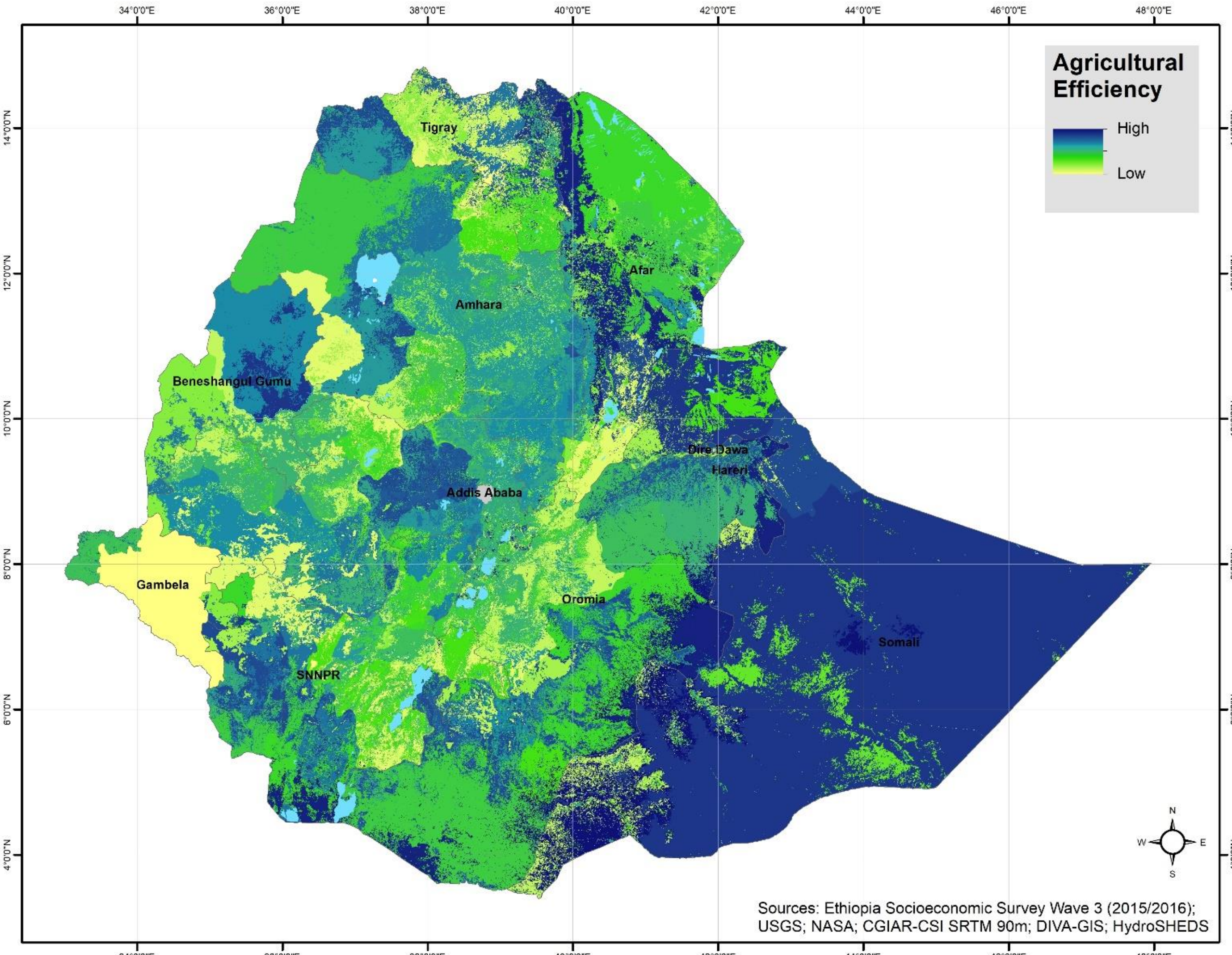
Our typology tools can also help to identify where agriculture has a better chance of getting people out of poverty in the most effective manner. For this section, we use the 2015/16 poverty measures calculated by the Planning and Development Commission of the Government of Ethiopia.[9] **Error! Reference source not found.** shows the rural poverty map for Ethiopia, which depicts the rural poverty headcount ratio, i.e., how many people living in rural areas of a region are below the poverty line (7,184 Birr) as a proportion of that region's total rural population. At the national level 27.1% of the rural population lives below the poverty line, with most regions reporting rural poverty rates within 5 percentage points of that value, except for SNNP (21.9%) and Harari (8.5%).[10] While **Error! Reference source not found.** shows the incidence of rural poverty in Ethiopia, **Error! Reference source not found.** shows the regional rural poverty gap index. This index is a measure of the intensity of rural poverty, or how far, on average, the rural poor in each region are from the poverty line (as a proportion of the latter). Interestingly, the Somali region, which has the 3rd lowest rural poverty rate (22.3%) has the highest rural poverty gap index (9%)

[9] Planning and Development Commission (2018).

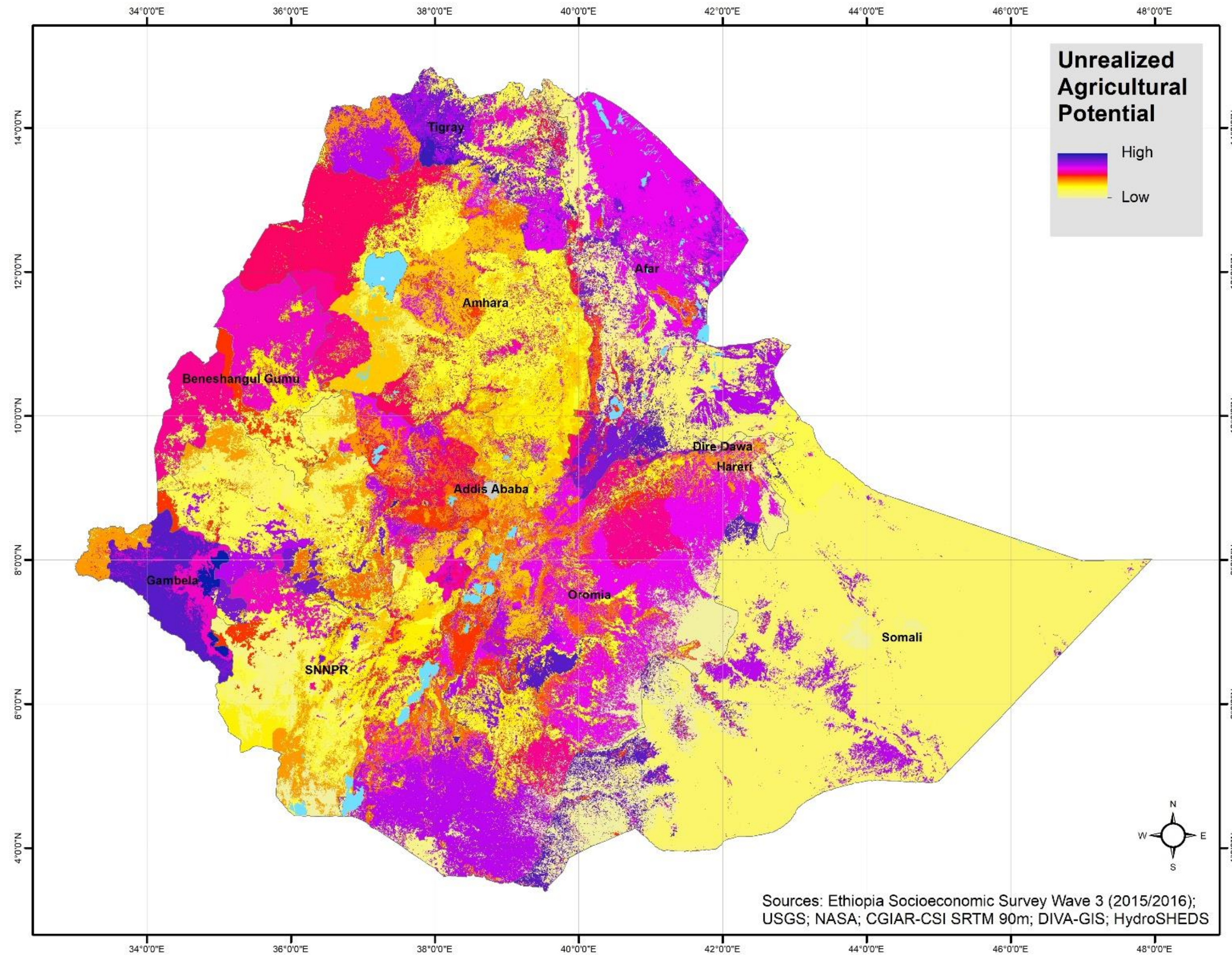
[10] For the rest of the regions the rural poverty rate ranged from 22.3% (Somali) to 31.1% (Tigray).

among all regions, higher even than Tigray's (8.2%), the region with the highest rural poverty rate in the country (31.1%).

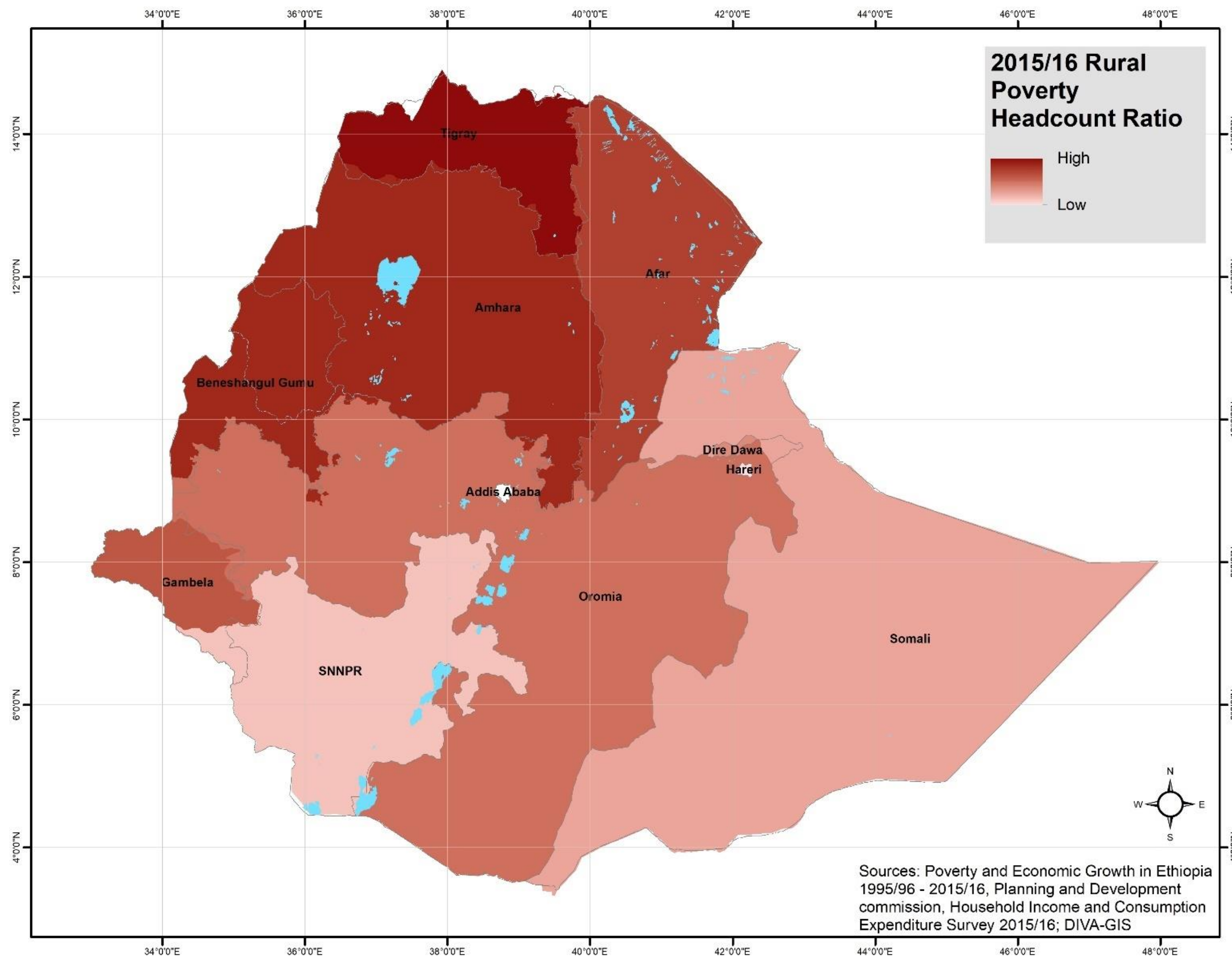
## Figure 10: Ethiopia: Agricultural profit efficiency



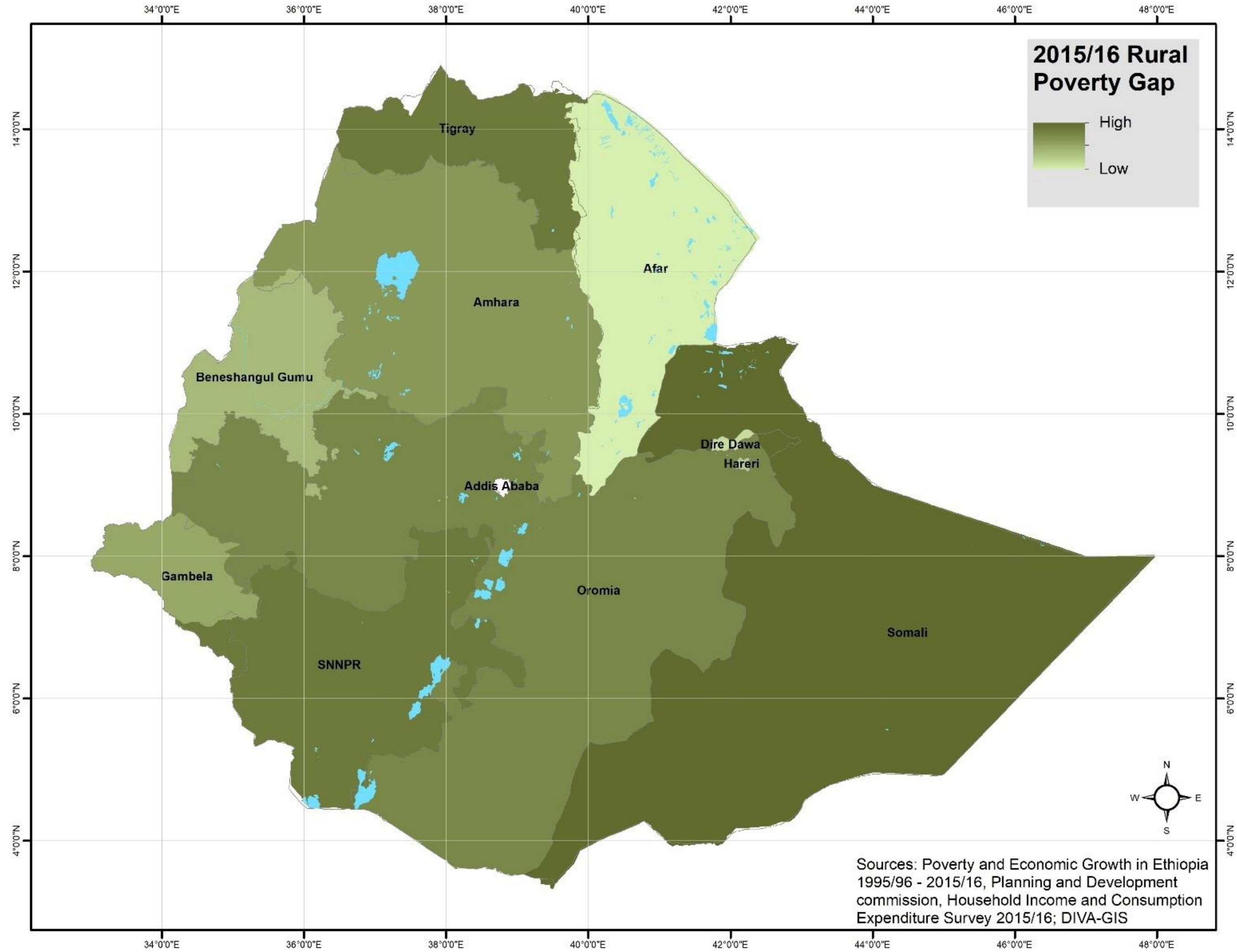
## Figure 11: Ethiopia: Unattained agricultural profit potential



## Figure 12: Ethiopia: 2015/16 Poverty map



## Figure 13: Ethiopia: 2015/16 Rural poverty gap index



**Error! Reference source not found.** shows how the SFA estimates of smallholder profit potential and efficiency underlying the construction of our typology can be used to assess the extent to which agriculture can help close the poverty gap:

- In areas where the poverty gap (average income of the poor minus the poverty line) is smaller than the efficiency gap (potential profit minus attained profit), the poverty gap can be closed by increasing smallholder efficiency.[11] This is shown in shades of purple in the map, darker shades indicate higher gains in efficiency are required.
- If the poverty gap is bigger than the efficiency gap, closing the poverty gap would require an increase in profit potential (in addition to gains in efficiency). This is shown in shades of red in the map, darker shades indicate larger gains in potential are required.
  - However, in some regions the increase in profit potential would have to be so large that it is reasonable to assume that agriculture is not the best suited tool to alleviate poverty there.

The results in the map show that for many regions in the country (in light purple), especially in the high central plateau, investing in increasing the efficiency of smallholders would be enough to close the poverty gap. In contrast, many areas in the Somali, Tigray, Afar, Oromia, and SNNP regions would require unrealistically high shifts in their agricultural potential due to its current low level combined in many cases with higher than average poverty gaps.

## 3.5 Scenario 1: Investing in irrigation

For this study, we use our typology results to assess how two different types of investments can increase rural households' incomes through an increase in the profitability of smallholder agriculture. The first scenario looks at the impact of an increase in access to irrigation through river diversion methods. The SFA approach allows us to estimate what would be the increase in the frontier, i.e., smallholder profit potential, (Table 3) associated to having access to irrigation through river diversion by *switching on* this indicator variable for observations that currently do not have access to it. However, switching on the river diversion irrigation indicator for *all* observations that currently do not have access to it is unrealistic due to hydrological and budget constraints. Instead, we analyze what would happen if we switch on the river diversion irrigation indicator only for areas that are within 20 kilometers of a surface water source (streams, rivers, lakes, wetlands, reservoirs, and creeks) and have slopes of 10% or less.

Under our SFA framework, improving smallholders' access to irrigation increases their agricultural profit potential, which in turn increases their current profits (↑ current profits = ↑ potential × efficiency) and the profits they could obtain in the future (↑ unattained potential = ↑ potential x [1 - efficiency]). The map in **Error! Reference source not found.** shows the increase in current profits, while the map in **Error! Reference source not found.** shows the increase in unattained potential. According to our analysis, the regions that would benefit the most from the river diversion irrigation expansion proposed in this scenario are Gambella and Afar.[12] For the average farmer in Gambella current annual farm profits would increase by 1,539 Birr while for Afar the increase would be of 554 Birr, which represent an increase of roughly 50% and 15% in farm profits respectively. The accompanying annual increase in unattained potential for

[11] Increasing the agricultural potential in these regions would also help to close the poverty gap (as attained profits are equal to potential profits times efficiency), but in general it is assumed investments to shift the potential are more expensive and require a longer time horizon.

[12] While other regions would benefit as well, this scenario would benefit a much larger portion of the area of Gambella and Afar.

the average farmer in the region would be of 6,081 Birr for Gambella and 1,225 Birr for Afar, which represent an increase in profit potential of about 12% and 3%.

## Figure 14: Ethiopia: Closing the poverty gap through investments in agriculture

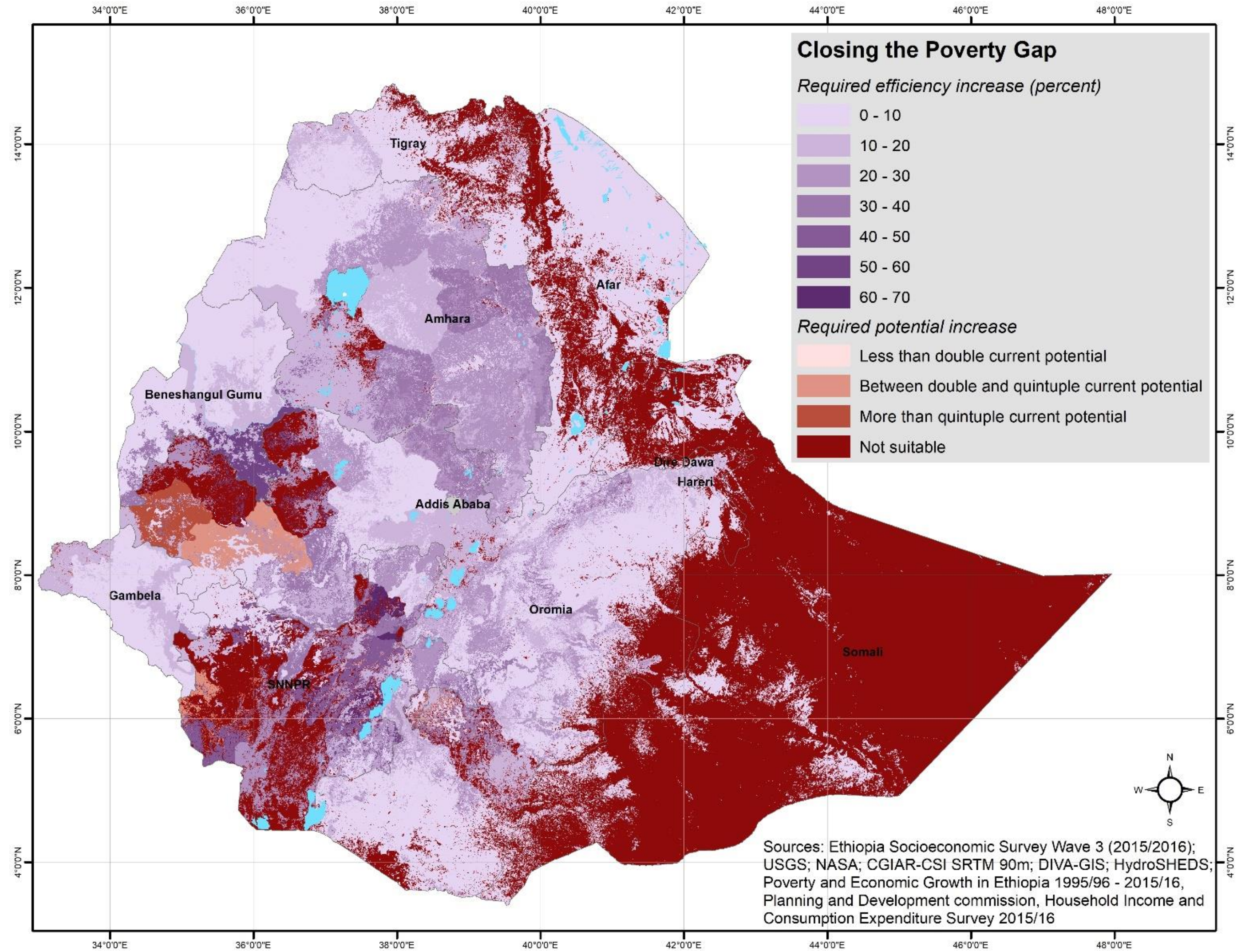
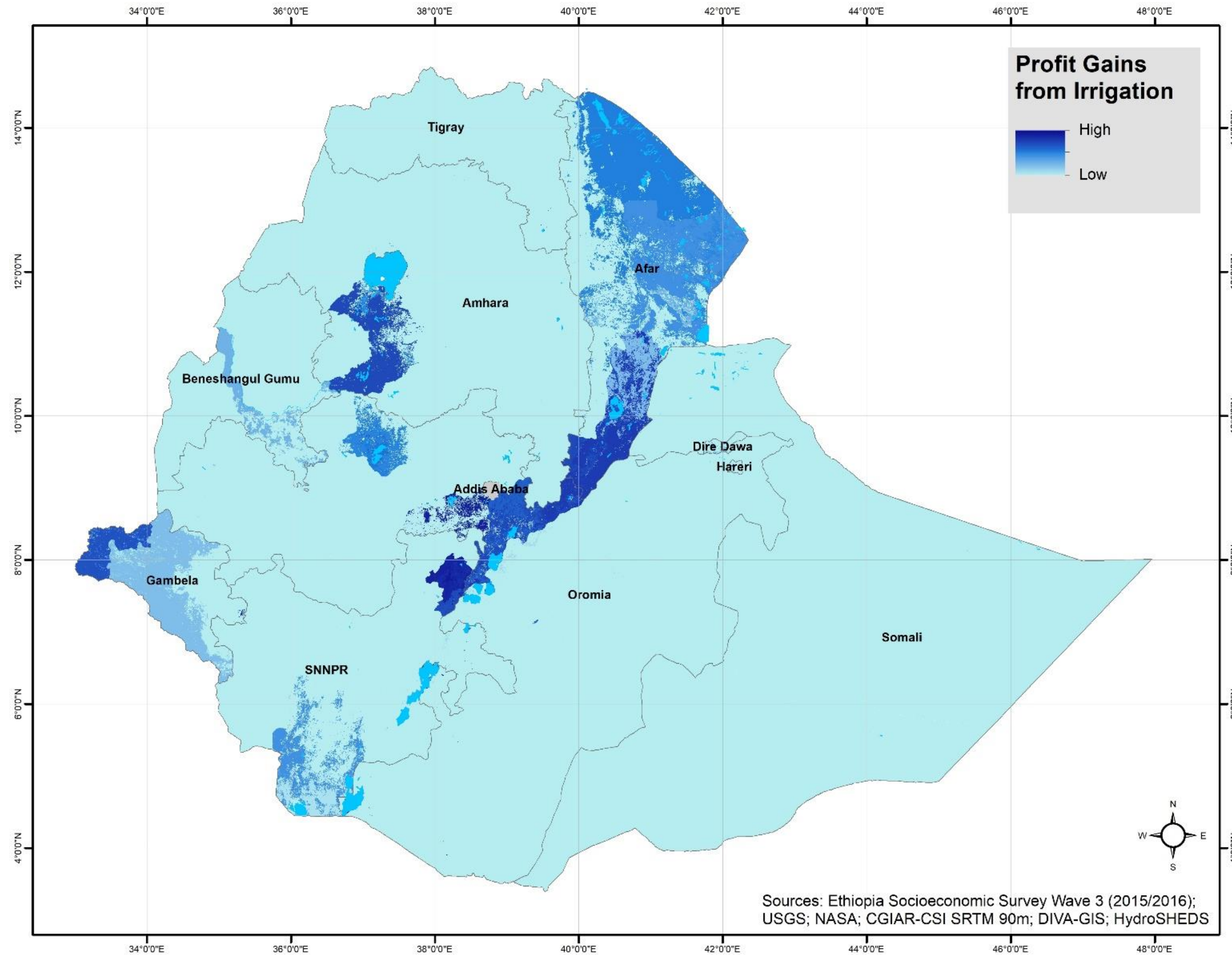
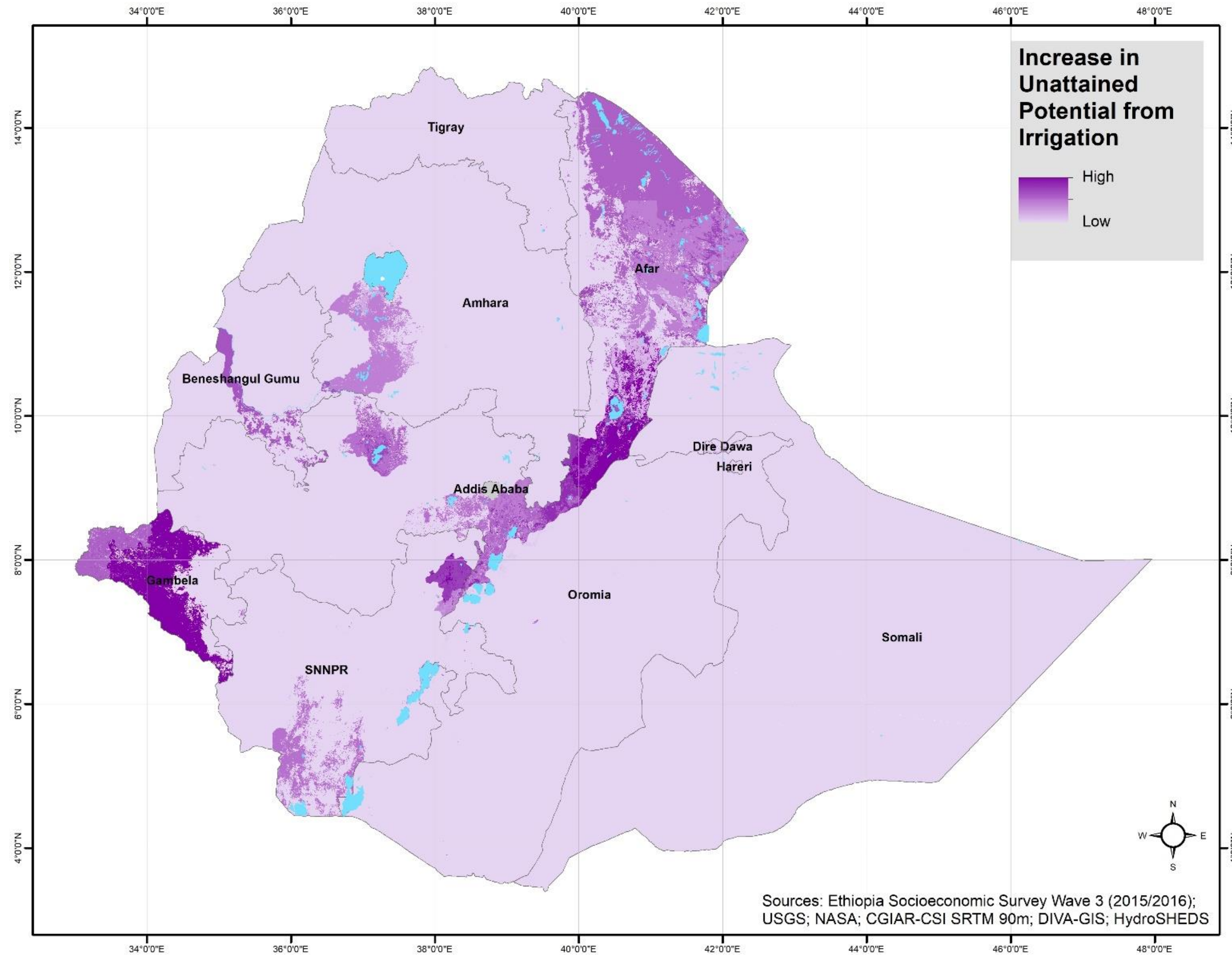


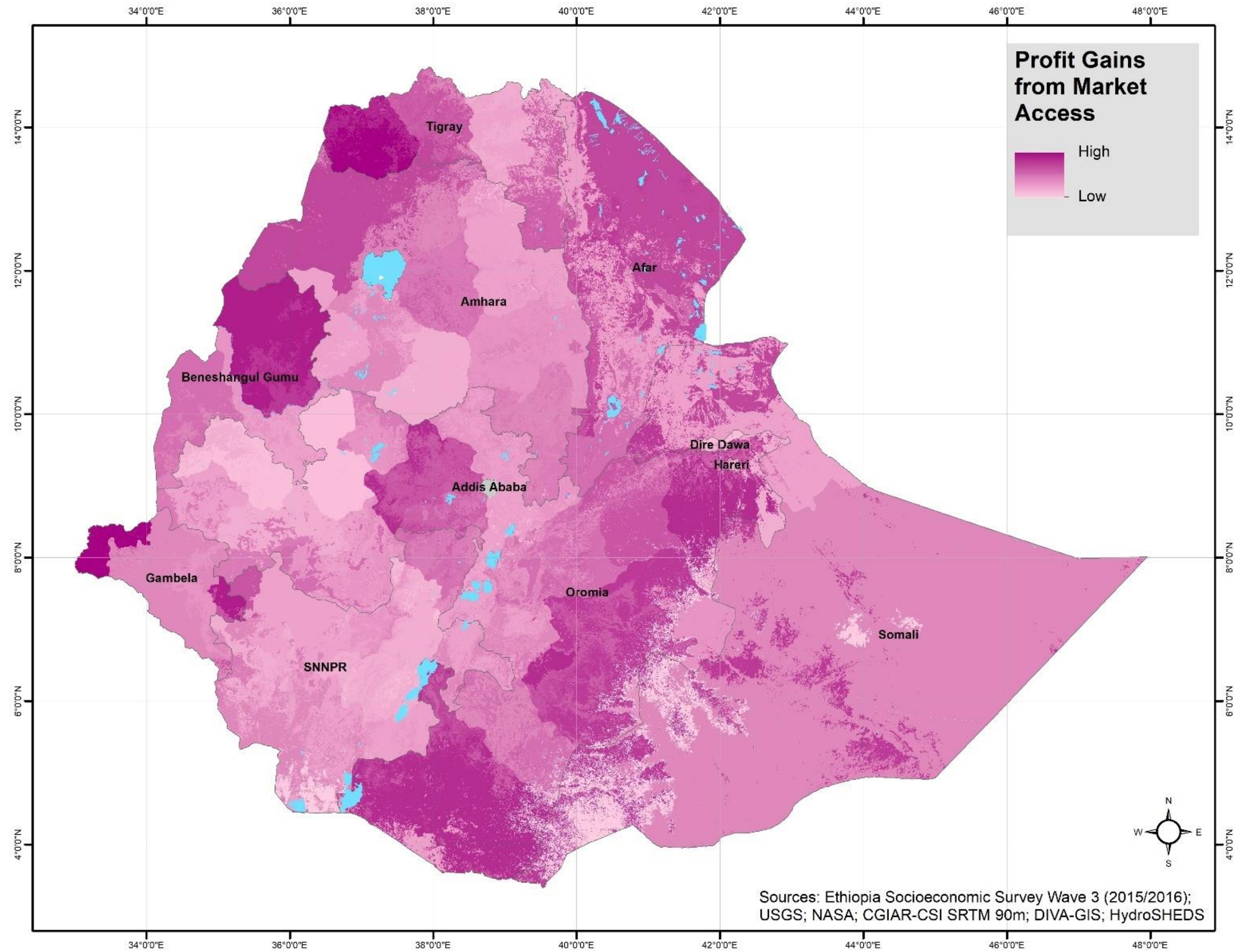
**Figure 15: Ethiopia: Current profit gains from increased irrigation access**



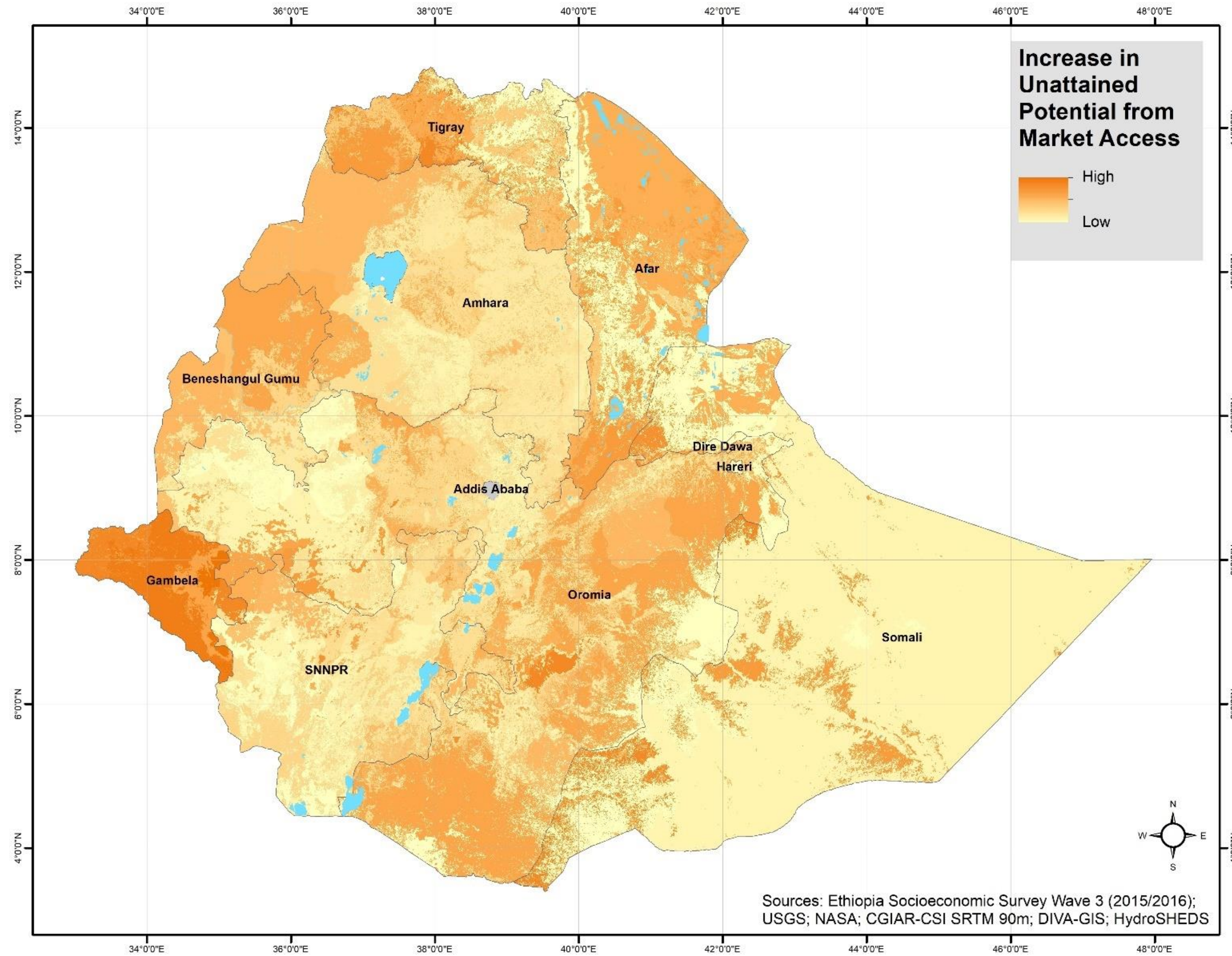
## Figure 16: Ethiopia: Unattained profit gains from increased access to irrigation



## Figure 17: Ethiopia: Current profit gains from increased market access



## Figure 18: Ethiopia: Unattained profit gains from increased market access



## 3.6 Scenario 2: Investing in market access

The second scenario looks at the impact of an increase in market access, which we simulate by analyzing what would be the impact of reducing travel time to the nearest market (city of least 25,000 inhabitants) from any farm in Ethiopia by 50%. Similarly to the irrigation case, under our SFA framework improving smallholders' access to markets increases their agricultural profit potential, which in turn increases their current profits (↑ current profits = ↑ potential × efficiency) and the profits they could obtain in the future (↑ unattained potential = ↑ potential x [1 - efficiency]). The map in **Error! Reference source not found.** shows the increase in current profits, while the map in **Error! Reference source not found.** shows the increase in unattained potential. According to our analysis, the region that would benefit the most from having its travel time to markets halved is Gambella, followed by Afar and Tigray. For the average farmer in Gambella current annual farm profits would increase by 3,237 Birr, while for Afar and Tigray the increase would be of 1,161 Birr and 1,012 Birr respectively, which more than doubles current average farm profits in Gambella and roughly increases profits in Afar by a third and in Tigray by a quarter. The accompanying annual increase in unattained potential for the average farmer in the region would be of 14,821 Birr for Gambella, 1,161 Birr for Afar, and 1,012 Birr for Tigray, which represent an increase in profit potential of 29%, 7%, and 8% respectively.

# 4 RESULTS FOR MALAWI

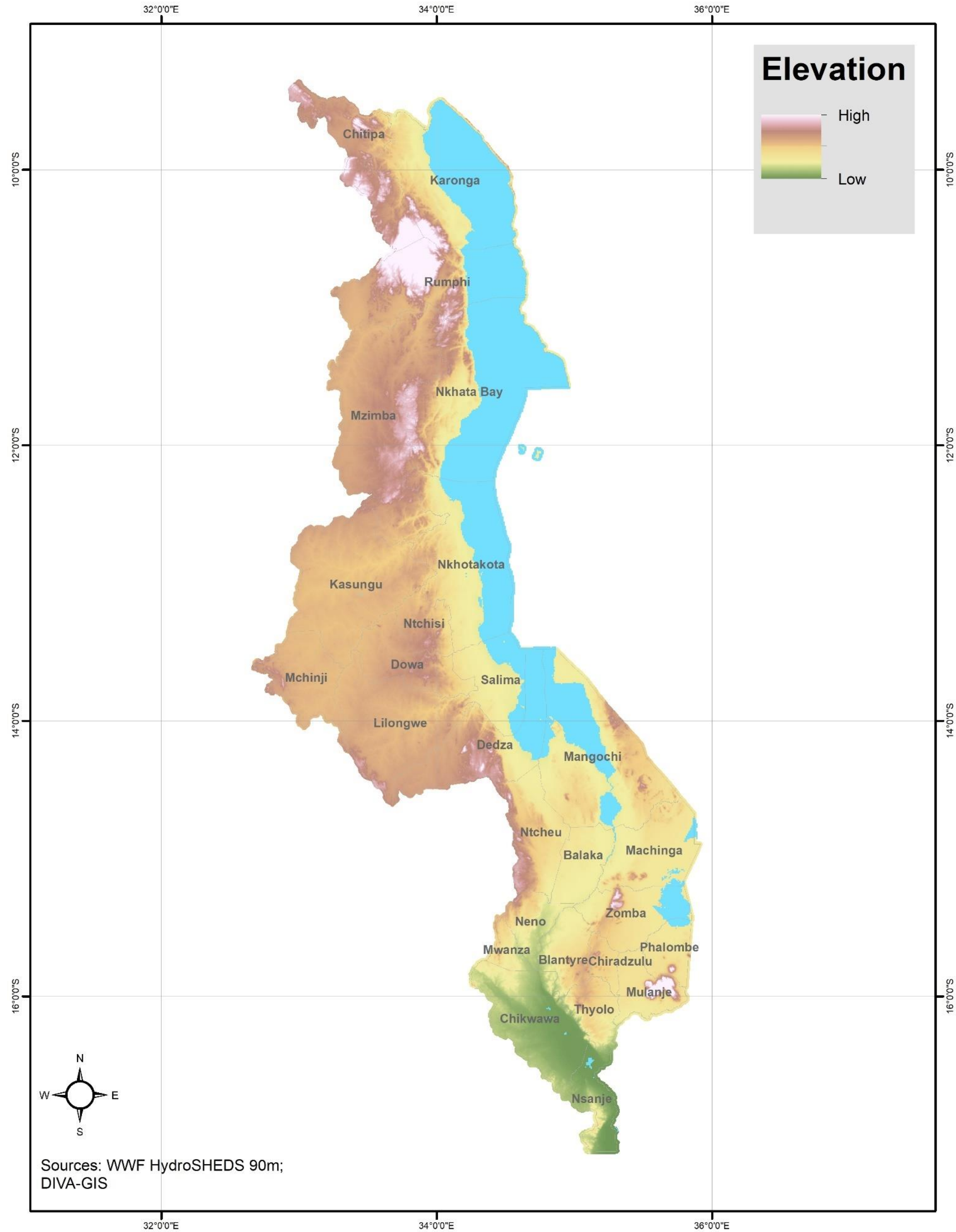
## 4.1 Spatial heterogeneity

**Error! Reference source not found.** shows the elevation map for Ethiopia. The country's geography lies within the Great African Rift Valley system, with Lake Malawi (the twelfth largest freshwater lake in the world) lying east side of the country. Much of the land surface of Malawi is a large plateau that is between 900 to 1,200 meters above sea level, but elevations rise over 2,400 meters in the Nyika Plateau in the north. The Shire highlands in the south are the lowest area in the country with elevations extending from 600 to 900 meters.

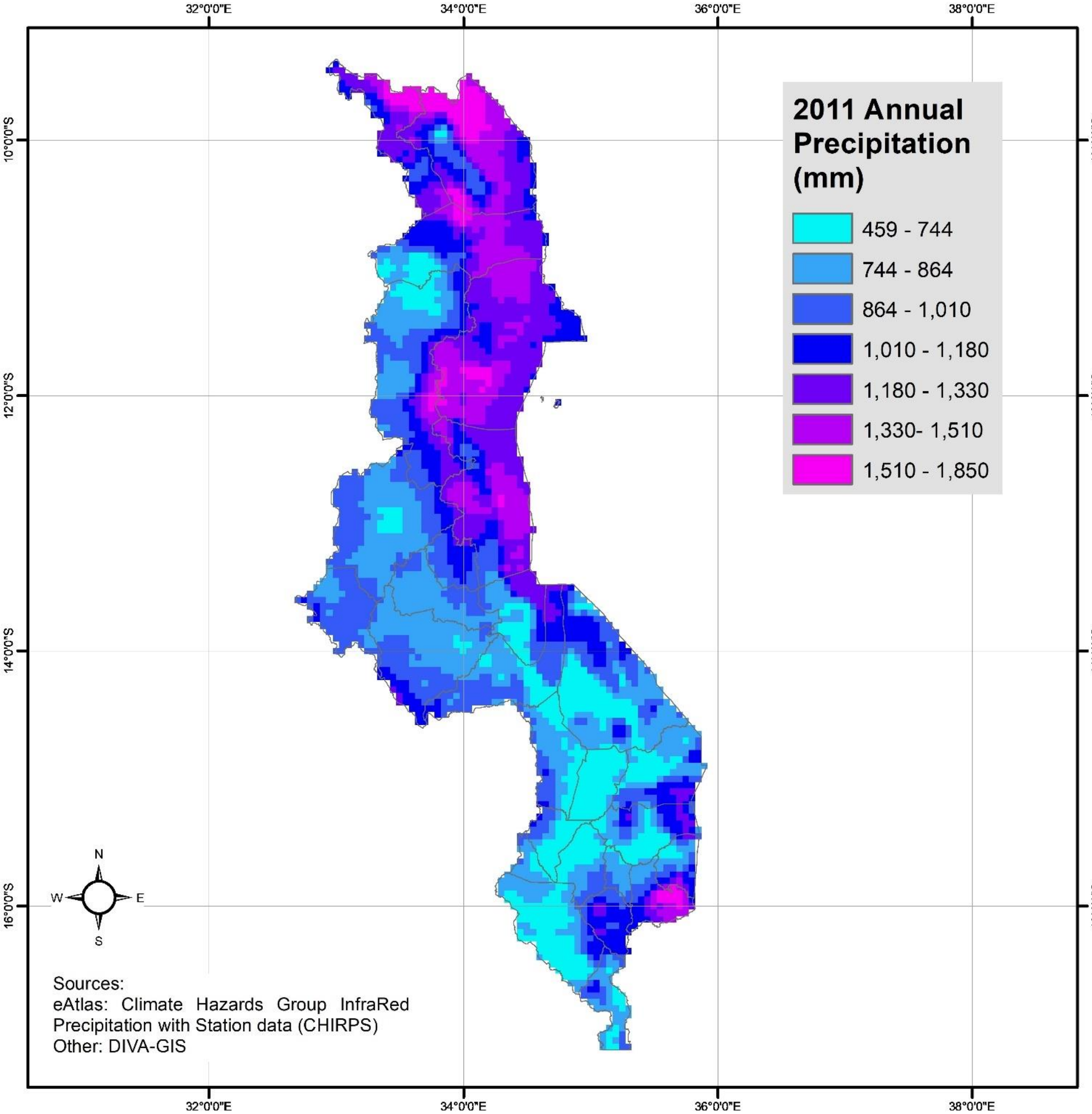
Annual precipitation for Malawi is shown in **Error! Reference source not found.**. In much of the country, annual precipitation is between 800 and 1,300 millimeters, and it's generally more abundant in the north and on the southern slopes of Mount Mulanje, where it can exceed 2,000 mm per year. Regarding soil quality, while the soil nutrient retention capacity map (**Error! Reference source not found.**) shows some variation between moderate and no constraints across the country, recent studies indicate that in many parts of Malawi the continuous application of inorganic fertilizers has created the threat of soil acidification, a process that lowers the capacity of soils to readily release its essential nutrient content to plants (Omuto & Vargas, 2018).

Beyond the biophysical conditions under which smallholders operate and which determine their productive capacity, their profitability greatly depends on their outputs reaching distant markets at a reasonable cost. **Error! Reference source not found.** illustrates the different levels of market accessibility across Malawi, as measured by the required travel time from any point in the country to the nearest city of 25,000 inhabitants or more. A clear pattern emerges highlighting the importance of each region's capital: Lilongwe in the Central Region, Mzuzu in the Northern Region, and Blantyre in the Southern Region.

## Figure 19: Malawi: Elevation



## Figure 20: Malawi: Annual precipitation (2011)



## Figure 21: Malawi: Soil nutrient retention capacity

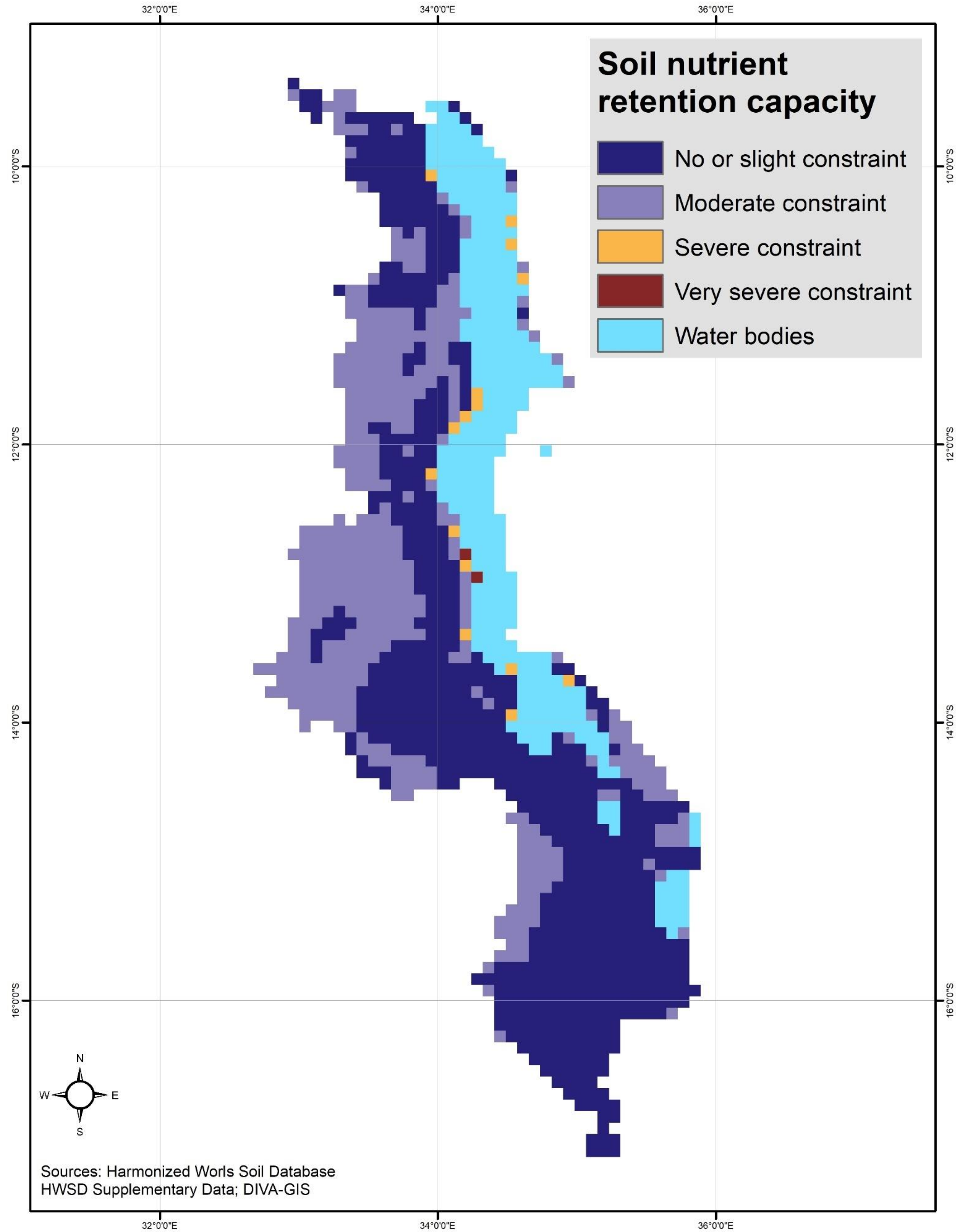
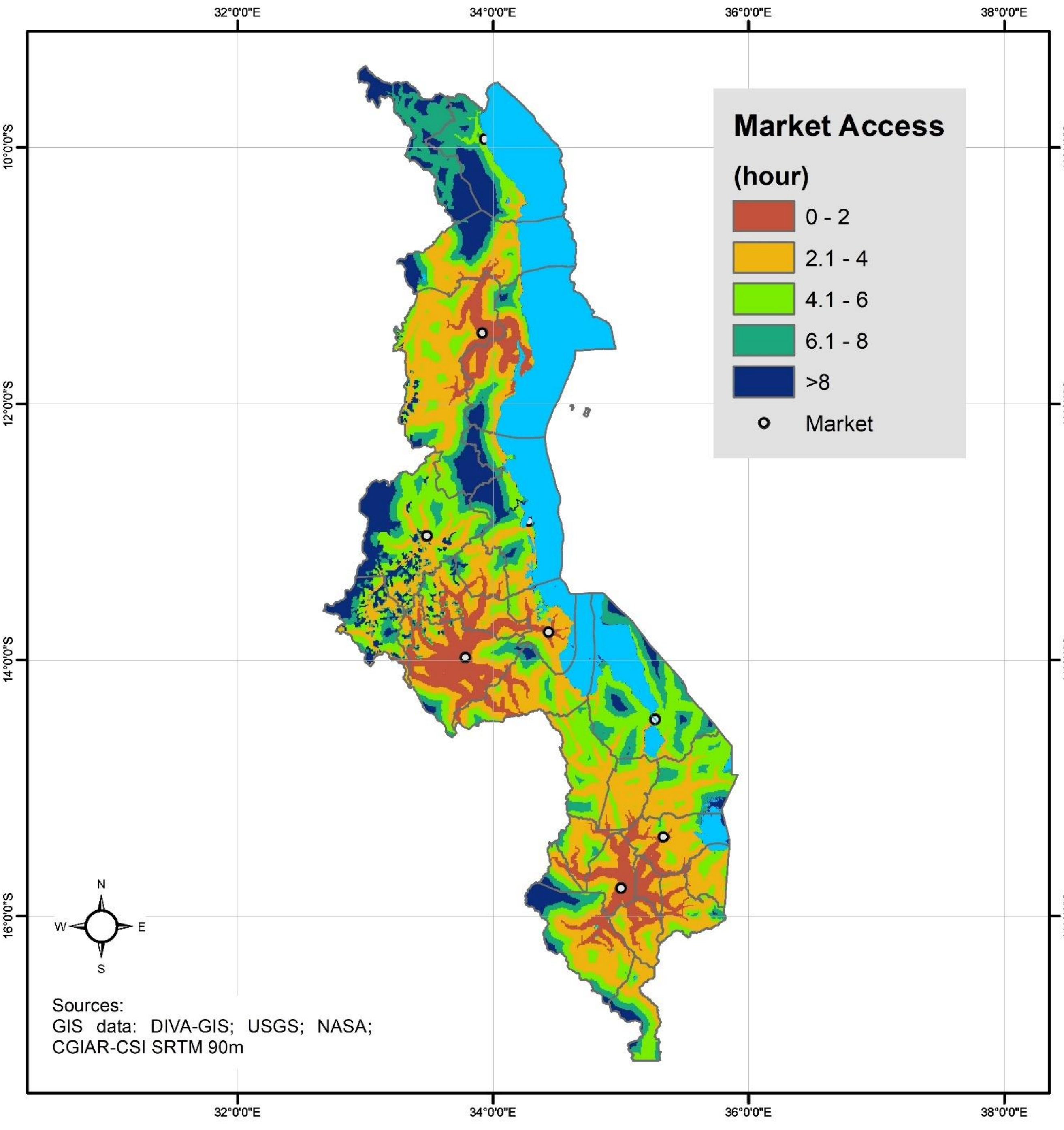


**Figure 22: Malawi: Travel time to the nearest city of 25,000 inhabitants or more**



The spatial heterogeneity in the distributions of different biophysical and economic factors that affect agricultural production and marketing translate to a high variation of farmgate prices for different crops across the country. **Error! Reference source not found.** shows the farmgate prices for maize in different regions of the country, with higher prices being observed in dark colored regions. The highest local prices for maize are observed in the northmost tip of the Northern Region (districts of Chitipa, Karonga, and Rumphi), which also suffer from the poorest levels of access to markets (**Error! Reference source not found.**). Underlying our estimates of agricultural profit potential and efficiency that are the main building blocks for our proposed typology is this high spatial heterogeneity in biophysical and economic conditions in which smallholders operate.

## 4.2 SFA estimation results

**Error! Reference source not found.** shows the results of the stochastic frontier estimation for Malawi.[13] The deterministic portion of the agricultural profit frontier is a function of input and output prices, AEZs (land use variables), access to irrigation (through river diversion), access to markets (travel time to the nearest city of 25,000 inhabitants or more), and additional GIS variables that measure the context in which smallholders operate. The factors influencing (the variance of) the non-negative component of the error term associated with farm efficiency are farm or community level irrigation investments, physical capital (land, farm assets), and human capital (household size, household head characteristics). The estimated coefficients from the regression in this table are used to predict regional level agricultural potential and efficiency.

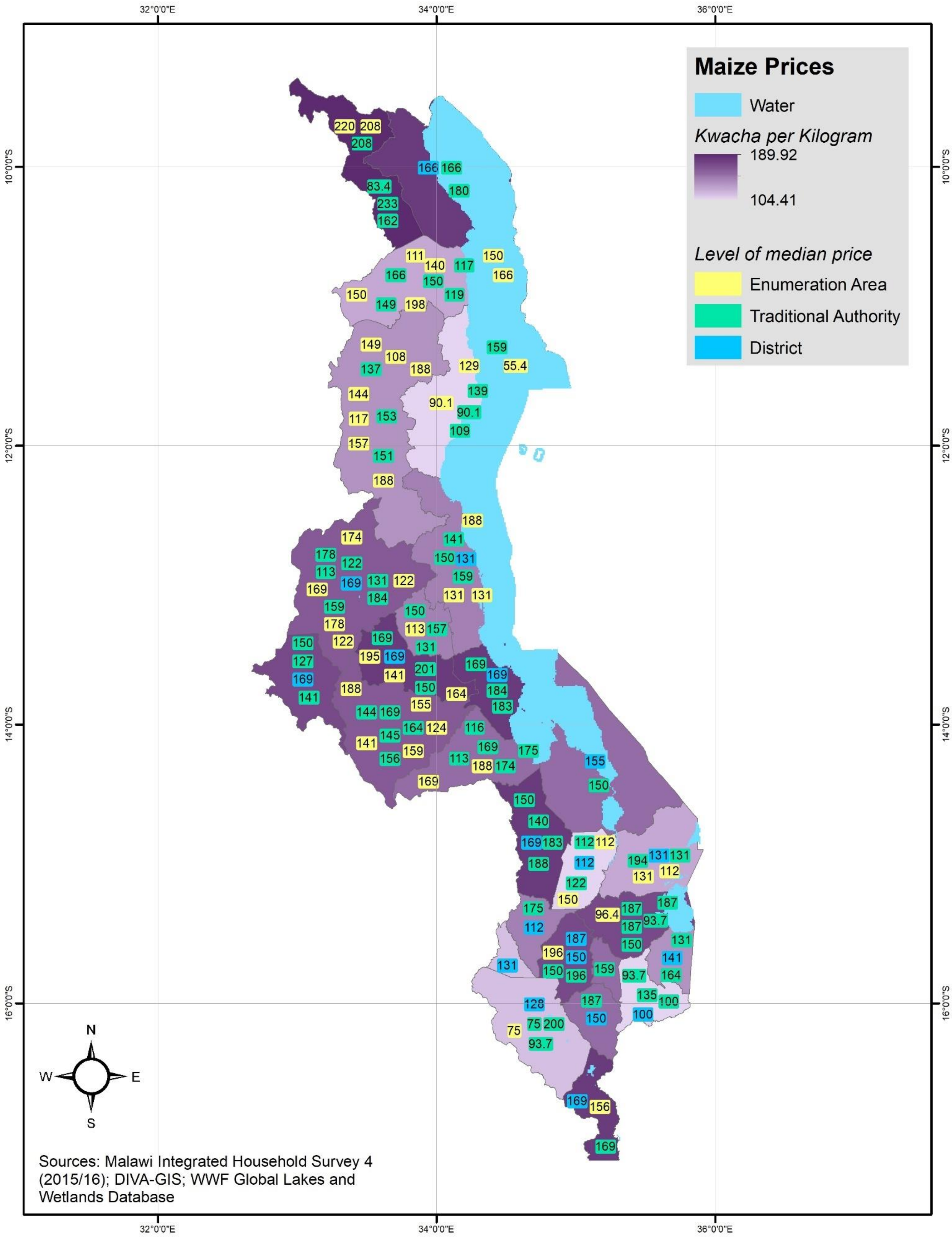
Our main interest for the irrigation and accessibility scenarios we want to assess are the coefficients for irrigation (river diversion) and time to market (hours). The positive and significant sign on the irrigation variable indicates that smallholders that reported having access to irrigation through river diversion have a higher profit frontier, i.e., higher profit potential. Conversely, the negative and significant sign on the time to market spline variables indicates that an increase in the distance between the farm and the nearest market is associated with a decrease in profit potential.

## 4.3 Agricultural potential and efficiency

**Error! Reference source not found.** shows the estimated potential for smallholder agriculture across Malawi, where agricultural potential is defined as the maximum profit that a farmer can gain from crop production if operating at maximum efficiency. 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. The southern region suffers from lower potential due to poorer general weather conditions and lower rainfall levels, which limit the length of the growing periods (less than 120 days in a year). The agricultural potential of a region can only be increased in the medium to long run through investments that shift the profit frontier such as R&D and technological innovations (e.g., new seed varieties, agricultural practices, production technologies, etc.) and large-scale infrastructure (irrigation, roads, electrification, ICTs, etc.).

[13] All variables measured in monetary values (Kwacha) are normalized using the price of maize (as explained in the Estimation section).

## Figure 23: Malawi: Farmgate prices for maize (Kwacha per kilogram)

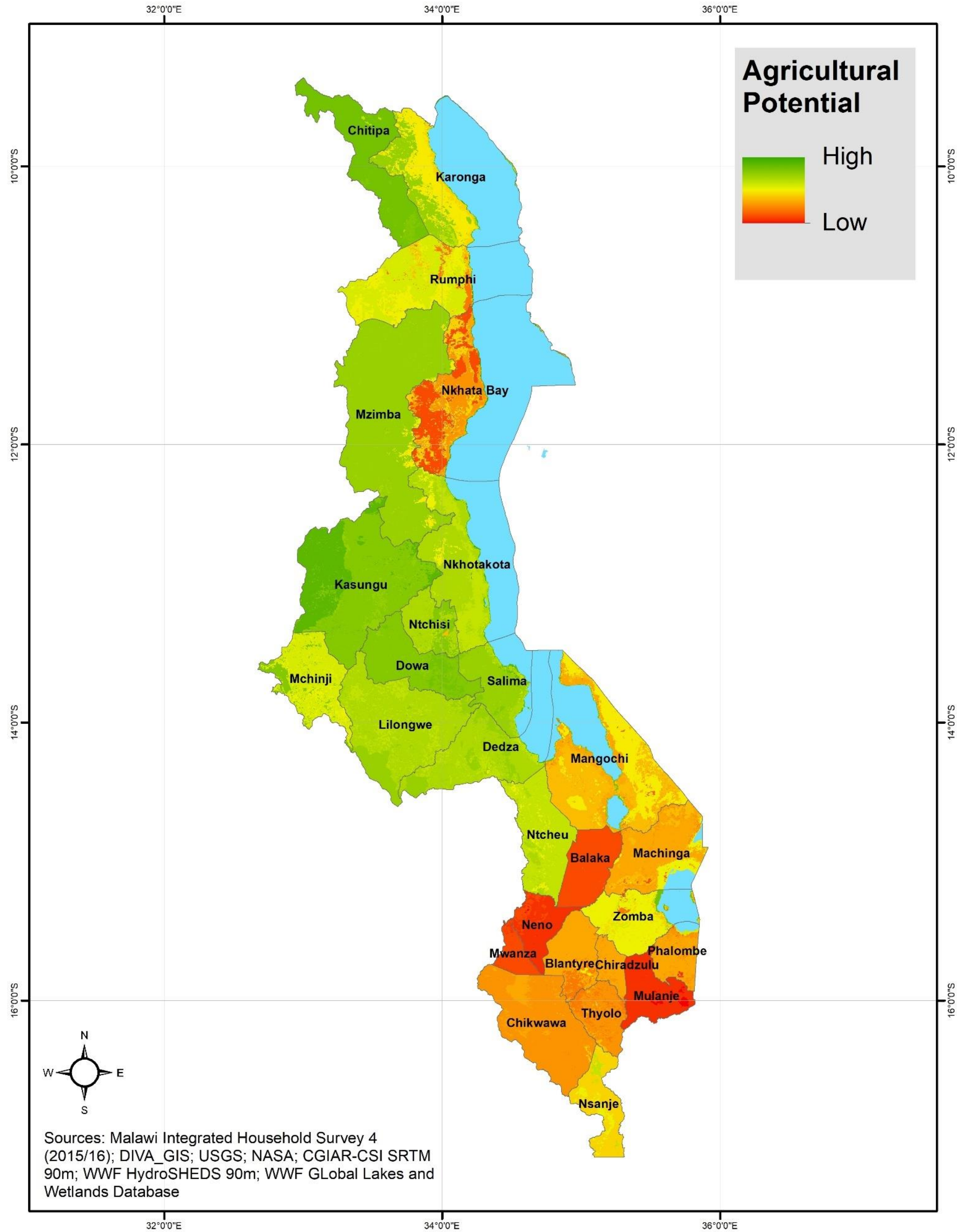


## Table 4: Malawi: SFA estimation

| *ln(Crop Profits)* | Coeff. | Std. Error |
|---|---|---|
| *Crop Prices* | | |
| Tobacco | 0.166 | 0.075** |
| Groundnuts | -0.180 | 0.157 |
| Beans | 0.037 | 0.159 |
| Soy | 0.110 | 0.197 |
| Pigeon pea | -0.144 | 0.228 |
| Rice | 0.441 | 0.120*** |
| *Seed Prices* | | |
| Maize | 0.231 | 0.072*** |
| Groundnuts | -0.323 | 0.129** |
| Beans | -0.574 | 0.212*** |
| Soy | - 0.136 | 0.241 |
| Pigeon peas | 0.114 | 0.140 |
| *Fertilizer Prices* | | |
| Urea | -0.742 | 0.341** |
| Chitowe | 0.431 | 0.363 |
| *Wages* | | |
| Men | 0.153 | 0.112 |
| Women | -0.151 | 0.111 |
| *Land Use* | | |
| Forest and closed shrubland | -0.281 | 0.321 |
| Woody savanna | 0.229 | 0.134* |
| Urban and wetlands | 0.218 | 0.380 |
| Croplands | -0.136 | 0.247 |
| Croplands / natural vegetation mosaic | -0.085 | 0.091 |
| *Geographic and environmental characteristics* | | |
| Slope | -0.022 | 0.024 |
| Annual precipitation (mm) | $-2.0\text{x}10^{-4}$ | $1.5\text{x}10^{-4}$ |
| Topographic wetness index | 0.005 | 0.012 |
| Elevation (m) | $3.0\text{x}10^{-4}$ | $1.3\text{x}10^{-4}$** |
| Nutrient retention capacity constraint | -0.015 | 0.029 |
| Irrigation: stream diversion | 0.747 | 0.222*** |
| *Time to market splines* | | |
| 0 - 2.5 hours | -0.023 | 0.086 |
| 2.5 - 5 hours | -0.017 | 0.044 |
| 5 - 7.5 hours | -0.029 | 0.028 |
| 7.5 - 10 hours | 0.003 | 0.024 |
| >10 hours | 0.008 | 0.016 |
| Constant | 11.729 | 0.425*** |
| $\boldsymbol{ln\sigma_v}$ | | |
| Constant | 0.539 | 0.045*** |
| $\boldsymbol{ln\sigma_u^2}$ | | |
| Irrigation: other method | 0.289 | 0.183 |
| Land ($m^2$) | $-1.7\text{x}10^{-4}$ | $-2.8\text{x}10^{-5}$*** |
| Farm asset value | -0.457 | 0.064*** |
| Household size | 0.016 | 0.034 |
| Maximum household education (years) | -0.067 | 0.018*** |
| Female head | 0.435 | 0.116*** |
| Constant | 3.061 | 0.236*** |
| $\sigma_v$ | 1.309 | 0.030 |
| N | | 3,296 |

*Sources: Malawi Integrated Household Survey 4 (2015/16); NASA; USGS; CGIAR-CSI SRTM90m; HydroSHEDS; WWF Global Lakes and Wetlands Database*

## Figure 24: Malawi: Agricultural profit potential



The spatial distribution of agricultural efficiency (**Error! Reference source not found.**) follows a similar pattern than the distribution of agricultural potential, with higher levels in the northern half of the country. Efficiency gaps can be closed through several short- and medium-term interventions that increase smallholders' productivity and will depend on what are the specific bottlenecks affecting each region. The unattained potential map (**Error! Reference source not found.**) 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 investments in those areas as well.

## 4.4 Poverty

Before assessing how investments in irrigation and roads would affect smallholder profits, we use our typology tools to identify where agriculture has a better chance of getting people out of poverty in the most effective manner. For this section, we use the 2016/17 poverty measures calculated by the National Statistics Office of Malawi and the Poverty and Equity Global Practice Group of the World Bank.[14] **Error! Reference source not found.** shows the rural poverty map for Malawi, which depicts the rural poverty headcount ratio, i.e., how many people living in rural areas of a region are below the poverty line (137,425 Kwacha) as a proportion of that region's total rural population. At the national level 59.5% of the rural population lives below the poverty line, with the rural South having the highest poverty rate (65.2%). While **Error! Reference source not found.** shows the incidence of rural poverty in Malawi, **Error! Reference source not found.Error! Reference source not found.** shows the regional rural poverty gap index. This index is a measure of the intensity of rural poverty, or how far, on average, the rural poor in each region are from the poverty line (as a proportion of the latter). Once again, the rural South has the largest poverty gap index at 23.2%, compared to the national rural index of 19.7%.

**Error! Reference source not found.** shows how the SFA estimates of smallholder profit potential and efficiency underlying the construction of our typology can be used to assess the extent to which agriculture can help close the poverty gap. The map shows that for all areas in the country, the poverty gap (average income of the poor minus the poverty line) is smaller than the efficiency gap (potential profit minus attained profit), so the poverty gap can be closed by increasing smallholder efficiency.[15] This is shown in shades of purple in the map, darker shades indicate higher gains in efficiency are required.

## 4.5 Scenario 1: Investing in irrigation

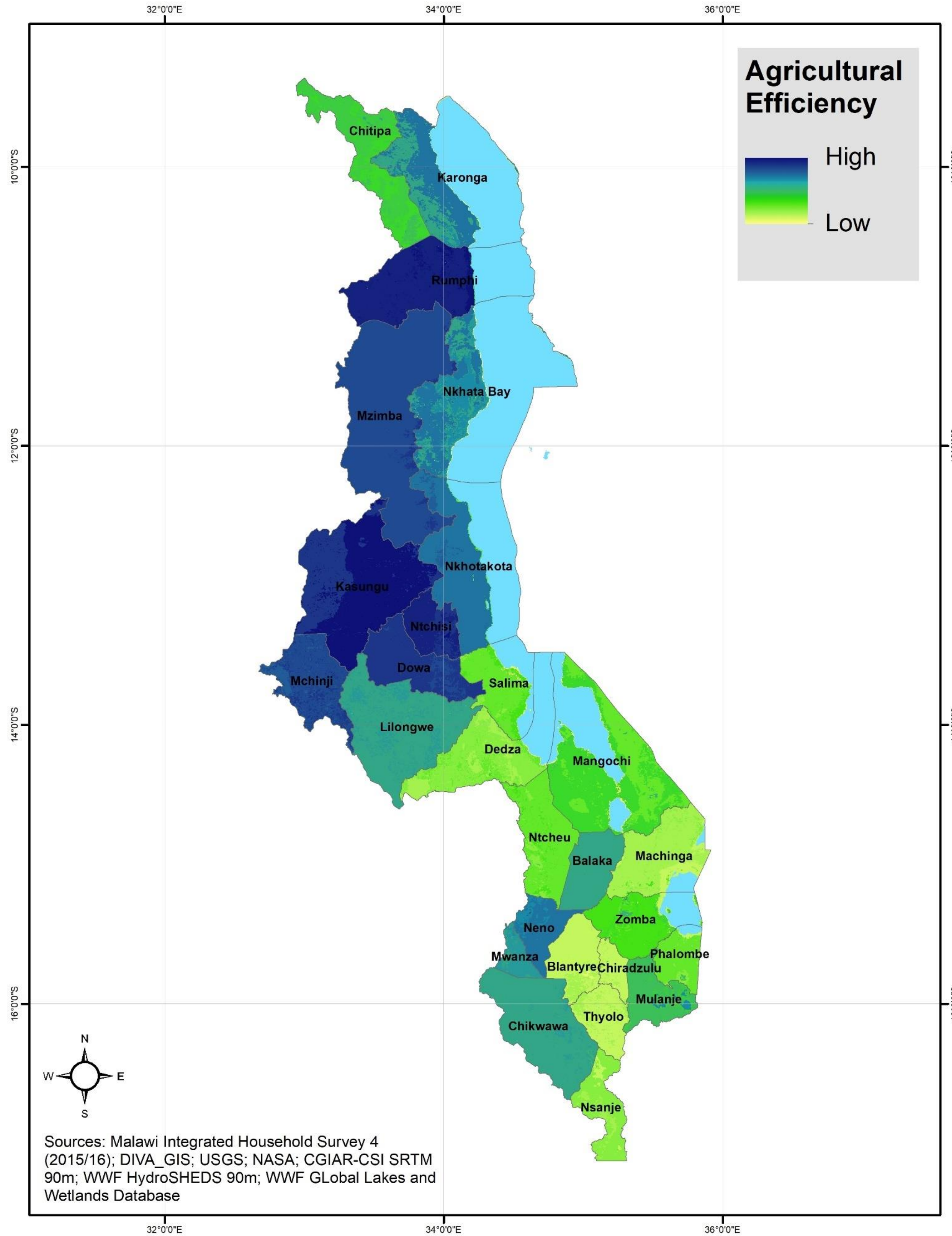
For this study, we use our typology results to assess how two different types of investments can increase rural households' incomes through an increase in the profitability of smallholder agriculture. The first scenario looks at the impact of an increase in access to irrigation through river diversion methods. The SFA approach allows us to estimate what would be the increase in the frontier, i.e., smallholder profit potential, (**Error! Reference source not found.**) associated to having access to irrigation through river diversion by *switching on* this indicator variable for observations that currently do not have access to it. However, switching on the river diversion irrigation indicator for *all* observations that currently do not have access to it is unrealistic due to hydrological and budget constraints. Instead, we analyze what would

[14] National Statistics Office of Malawi and the Poverty and Equity Global Practice Group of the World Bank (2018).

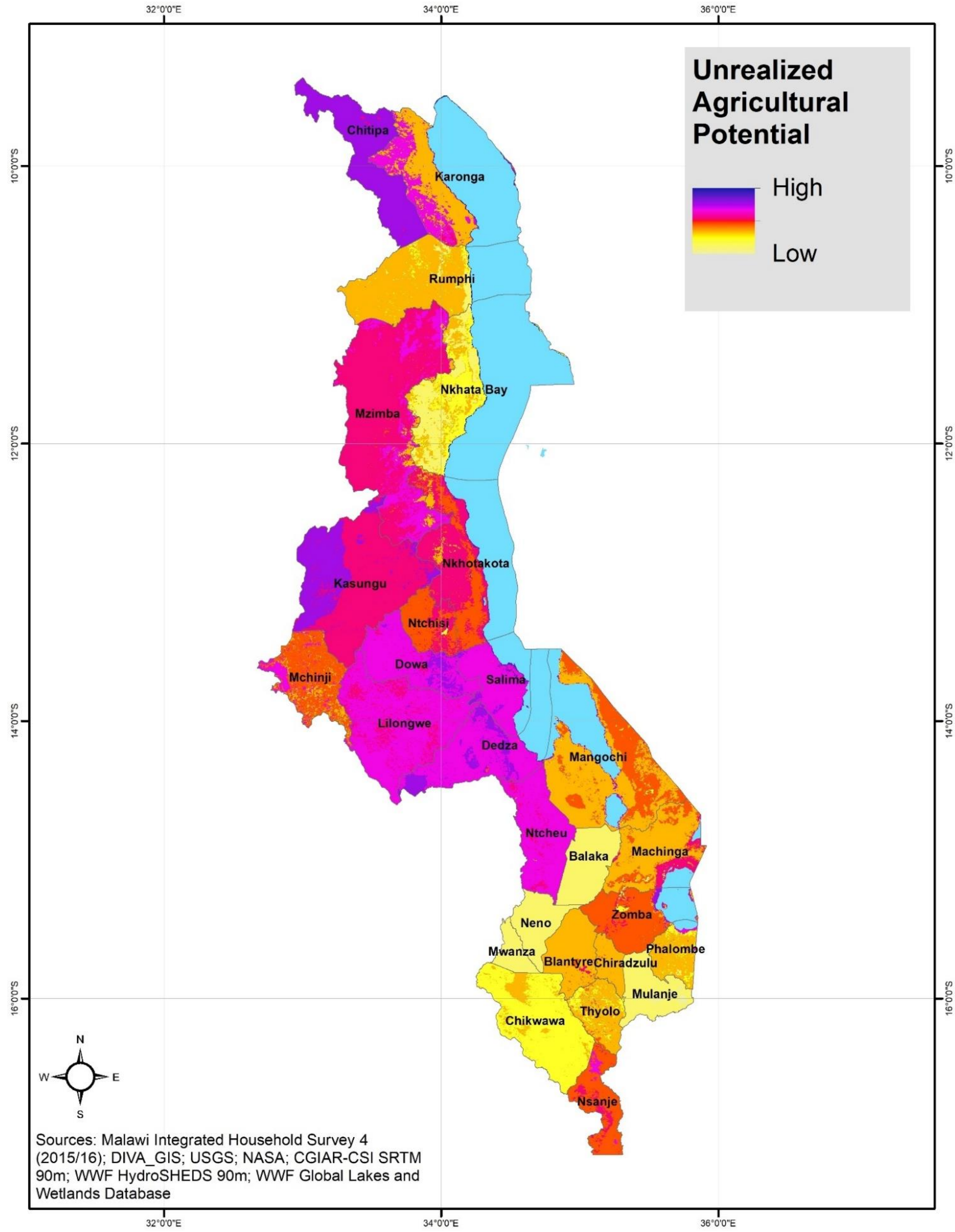
[15] Increasing the agricultural potential in these regions would also help to close the poverty gap (as attained profits are equal to potential profits times efficiency), but in general it is assumed investments to shift the potential are more expensive and require a longer time horizon.

happen if we switch on the river diversion irrigation indicator only for areas that are within 20 kilometers of a surface water source (streams, rivers, lakes, wetlands, reservoirs, and creeks) and have slopes of 10% or less.

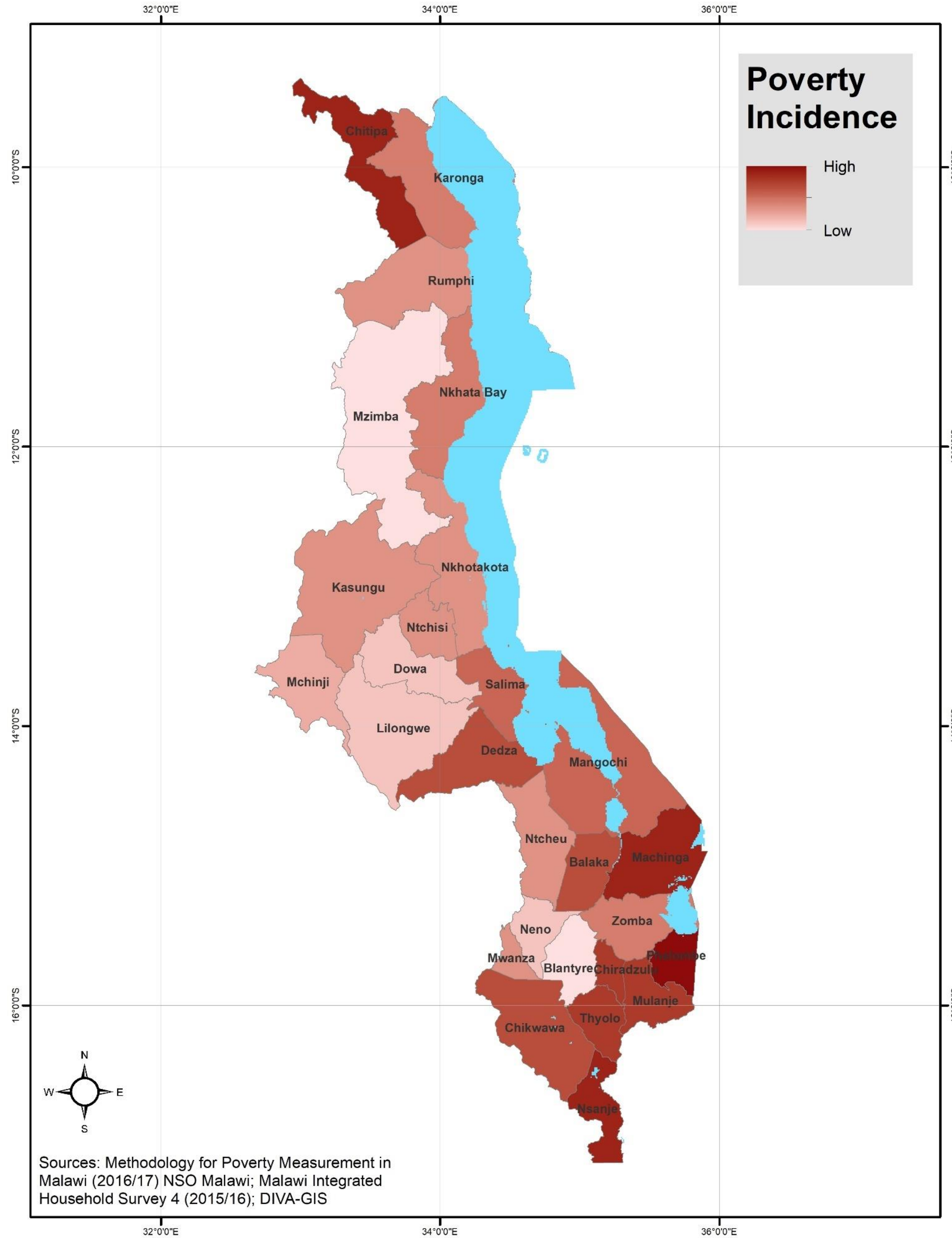
## Figure 25: Malawi: Agricultural profit efficiency



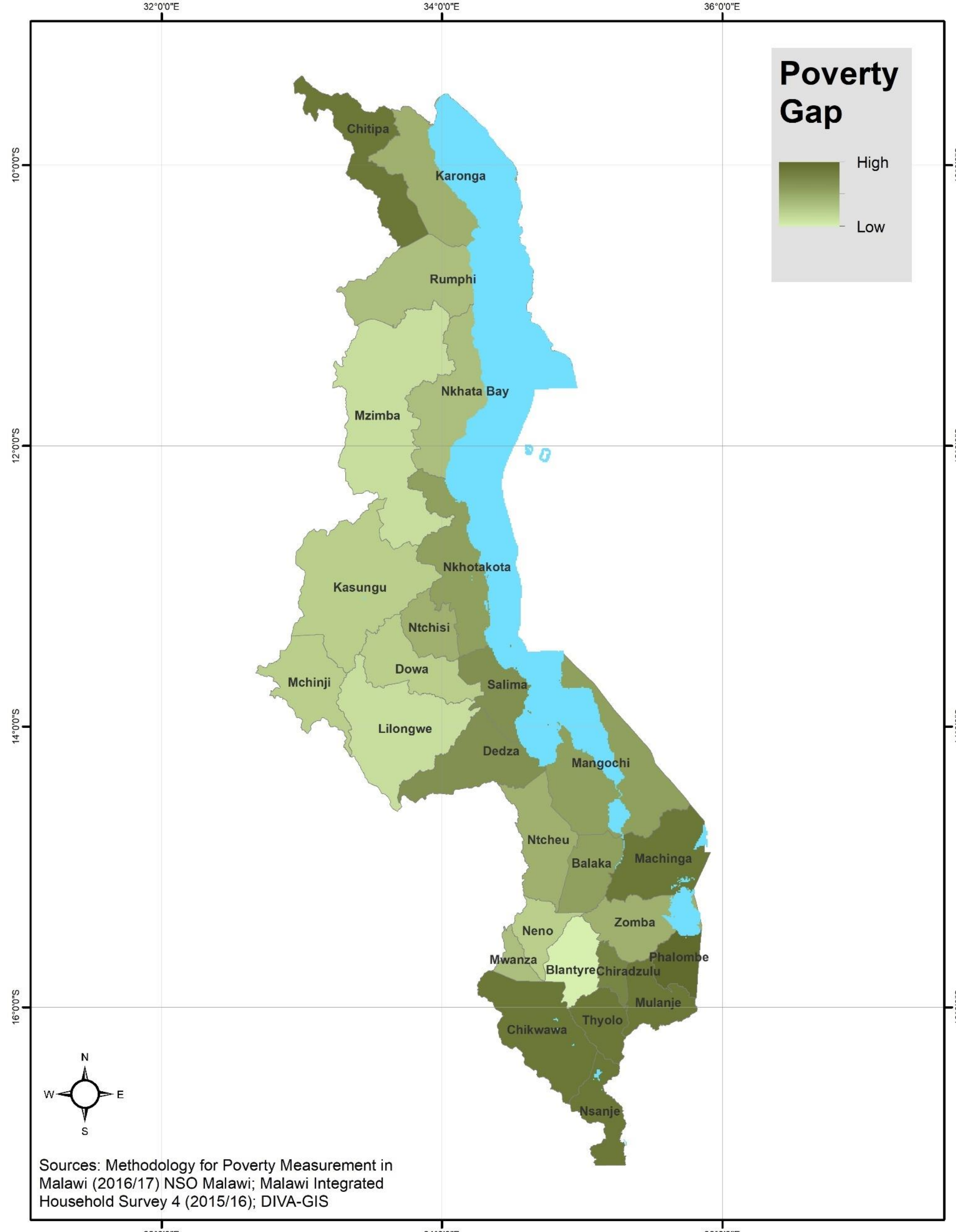
## Figure 26: Malawi: Unattained agricultural profit potential



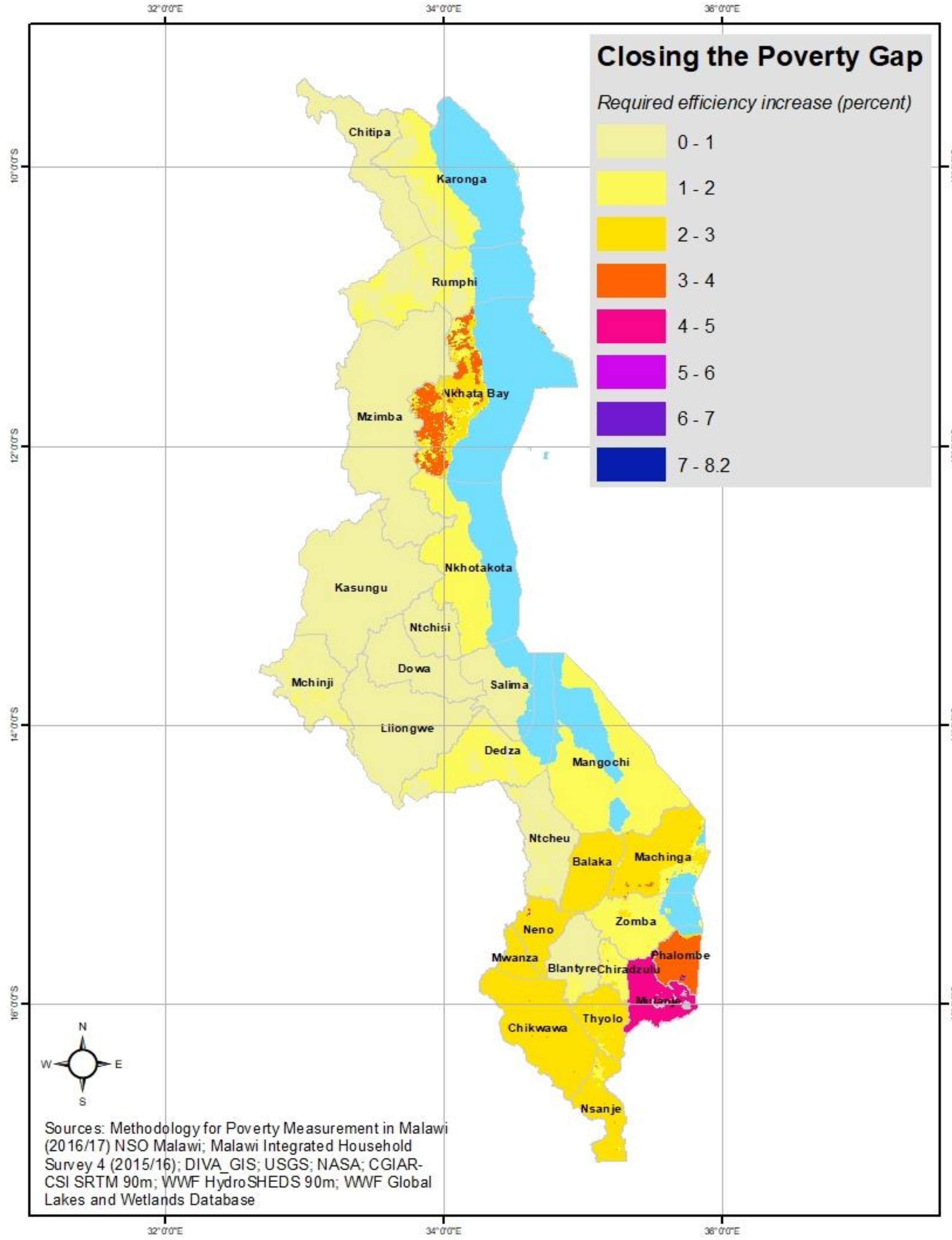
### Figure 27: Malawi: 2016/17 Poverty map



## Figure 28: Malawi: 2016/17 Rural poverty gap index



## Figure 29: Malawi: Closing the poverty gap through investments in agriculture



### Figure 30: Malawi: Current profit gains from increased irrigation access

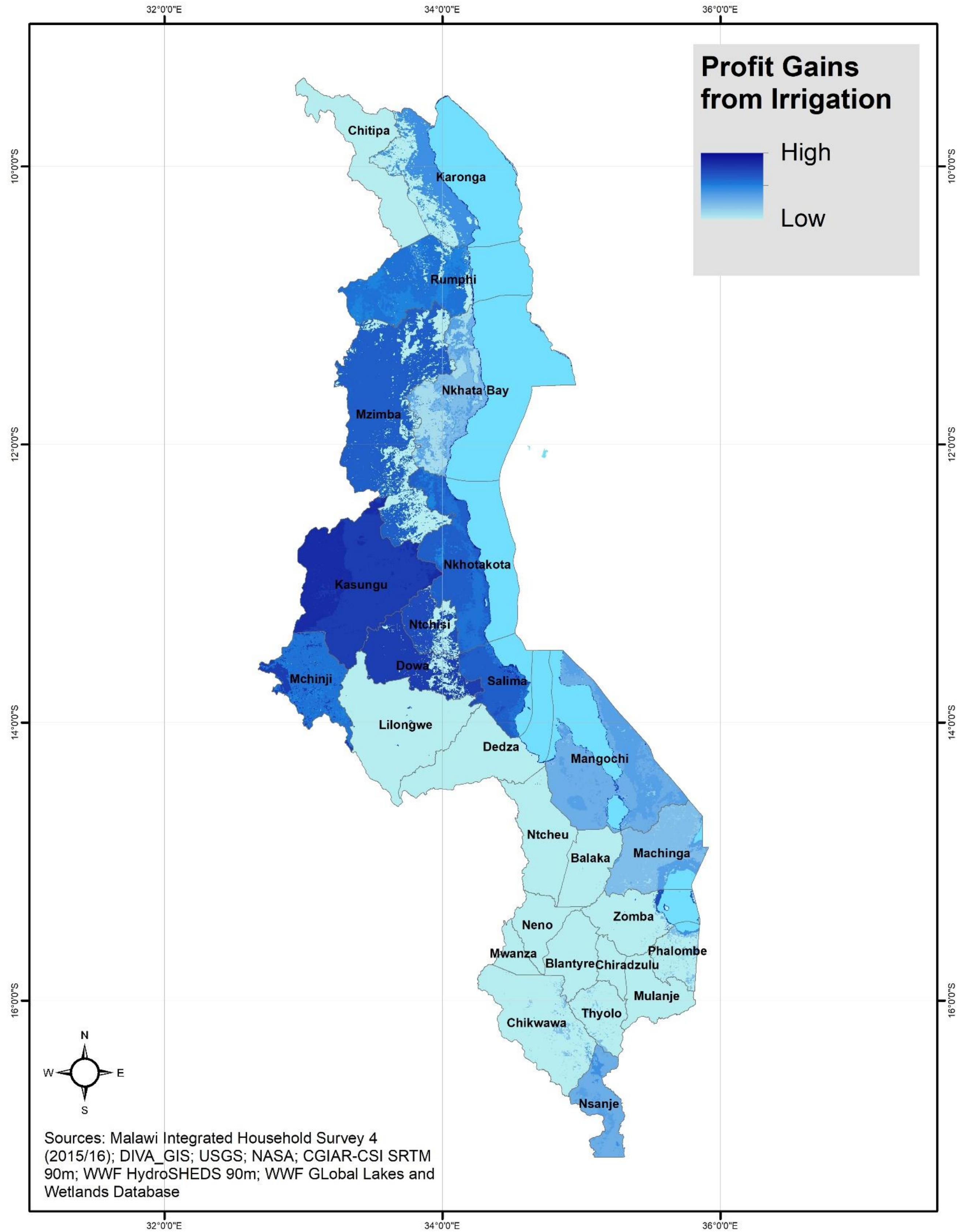
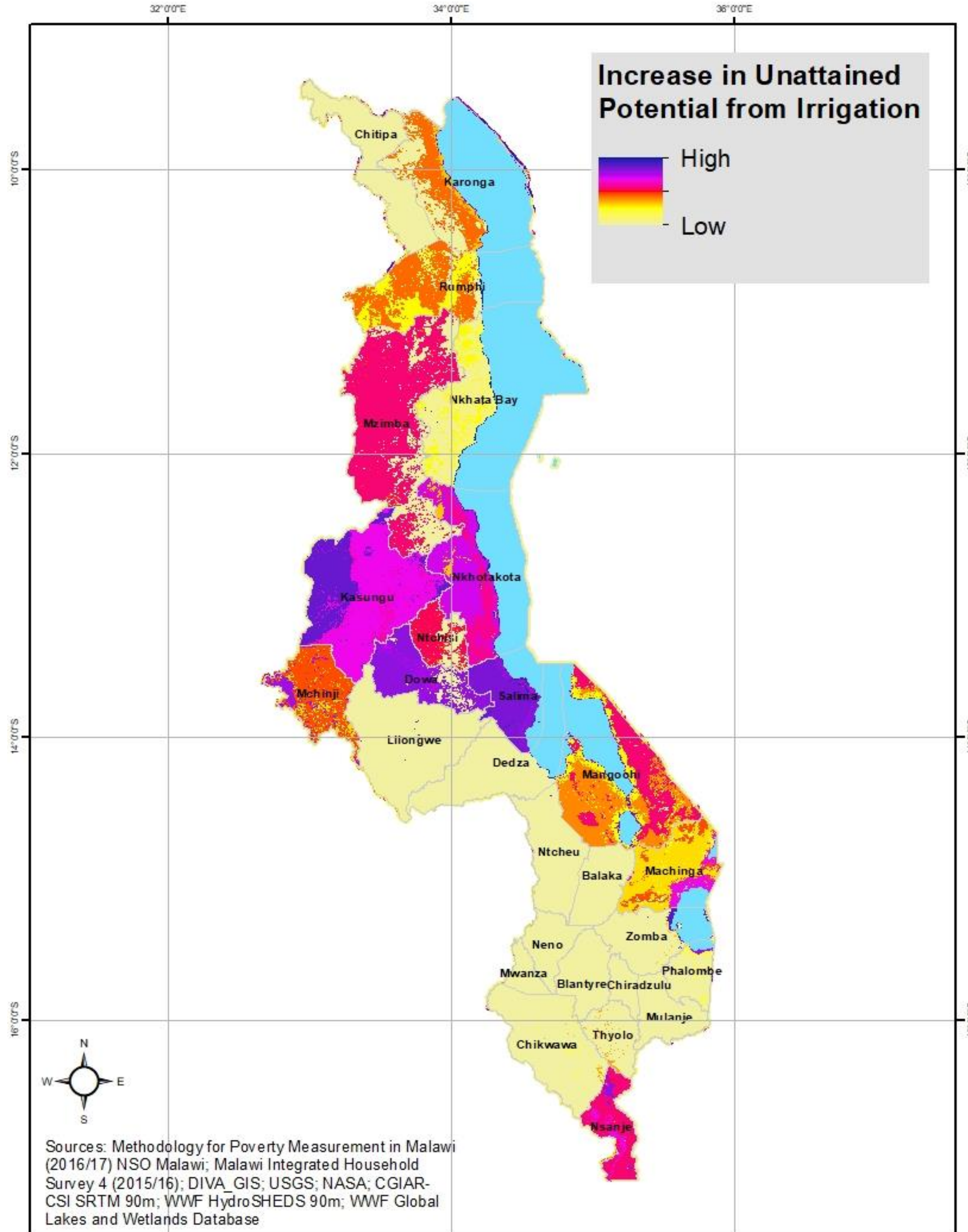
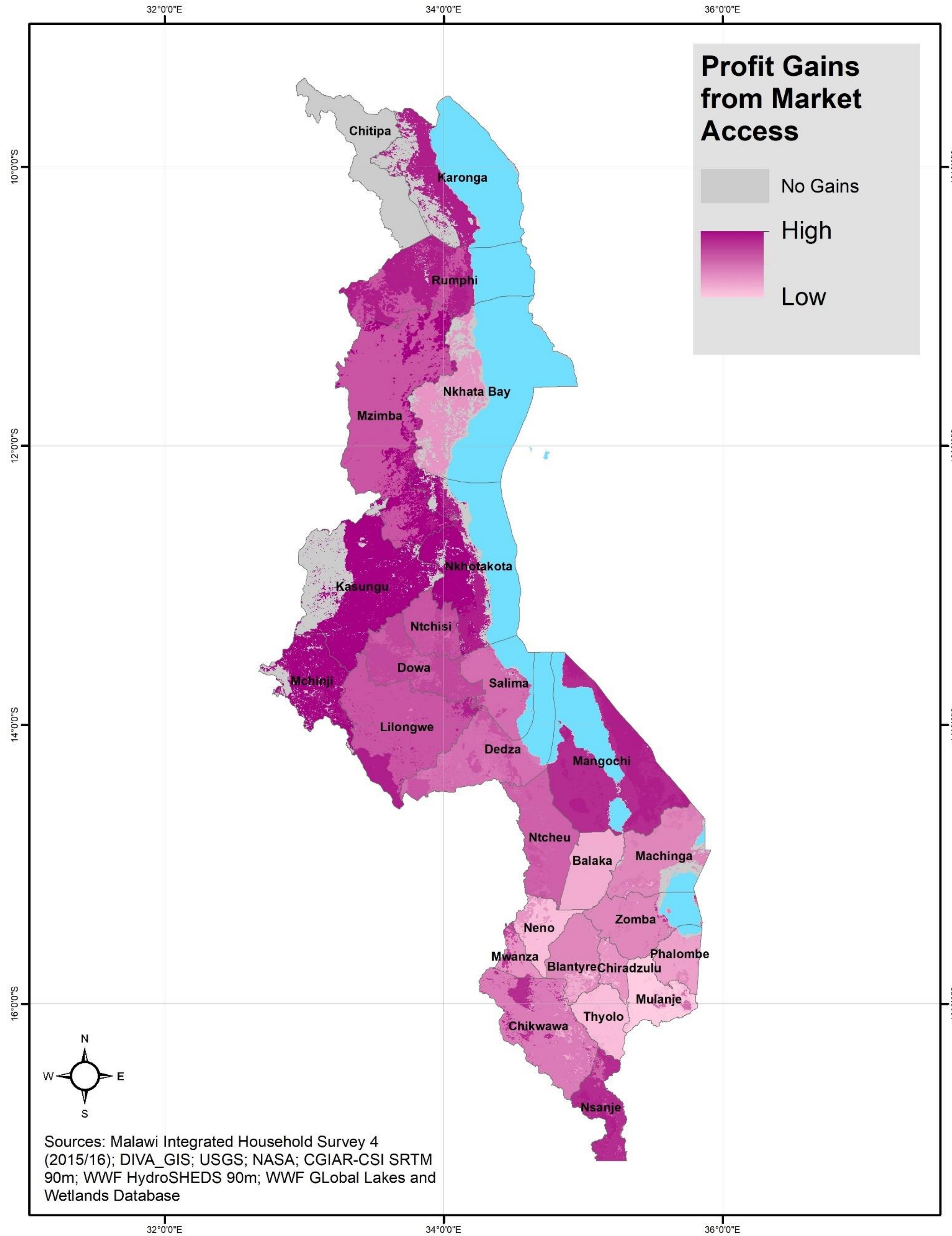


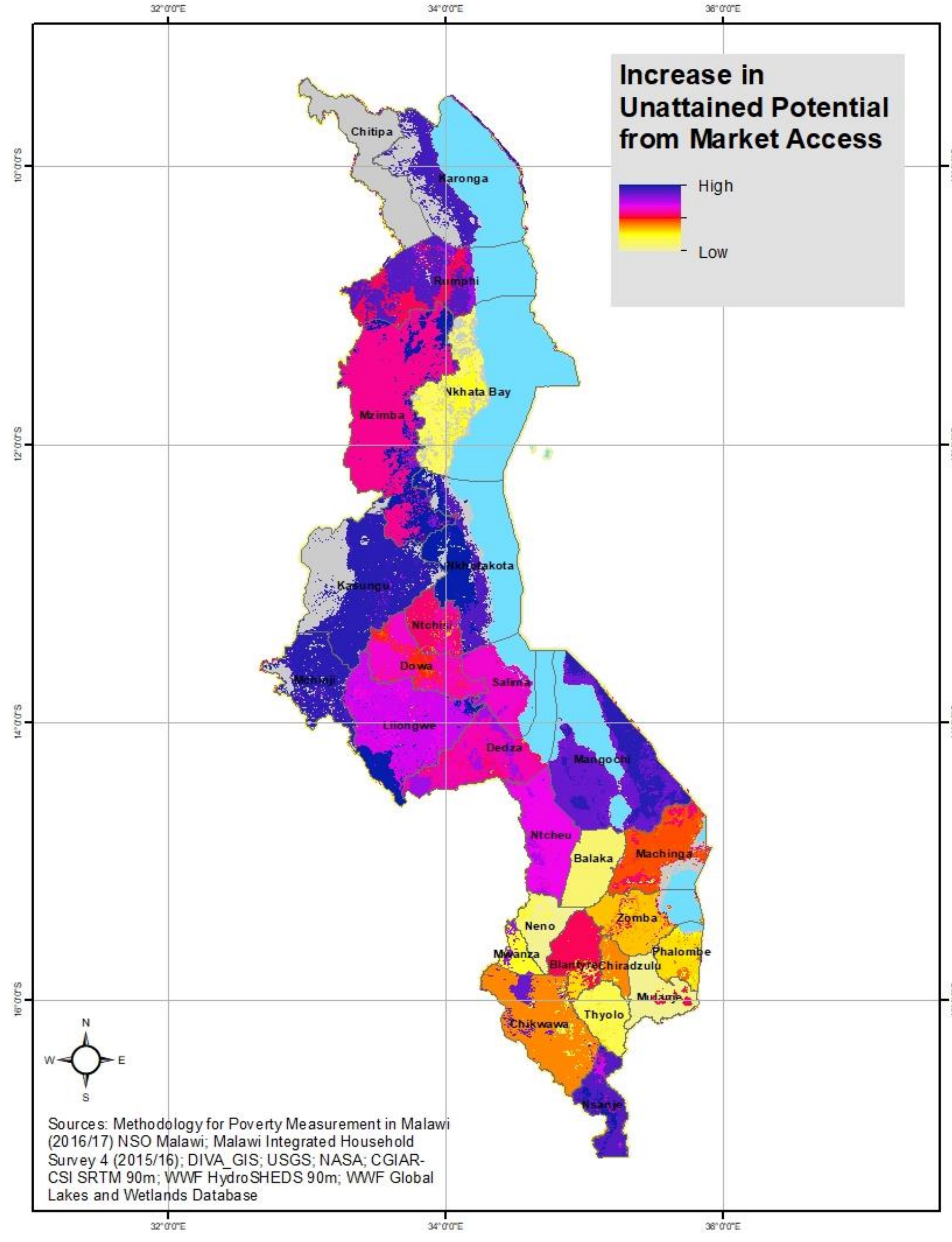
**Figure 31: Malawi: Unattained profit gains from increased access to irrigation**



## Figure 32: Malawi: Current profit gains from increased market access



## Figure 33: Malawi: Unattained profit gains from increased market access



Under our SFA framework, improving smallholders' access to irrigation increases their agricultural profit potential, which in turn increases their current profits (↑ current profits = ↑ potential × efficiency) and the profits they could obtain in the future (↑ unattained potential = ↑ potential x [1 - efficiency]). The map in **Error! Reference source not found.** shows the increase in current profits, while the map in **Error! Reference source not found.** shows the increase in unattained potential. According to our analysis, the region that would experience the largest increases in current profits is the Central Region, particularly the districts of Kasungu and Dowa. The increase in unattained potential from this irrigation expansion would also be larger for the Central Region, again in the districts of Kasungu and Dowa, as well as Salima.

### 4.6 Scenario 2: Investing in market access

The second scenario looks at the impact of an increase in market access, which we simulate by analyzing what would be the impact of reducing travel time to the nearest market (city of at least 25,000 inhabitants) from any farm in Malawi by 50%. Similarly to the irrigation case, under our SFA framework improving smallholders' access to markets increases their agricultural profit potential, which in turn increases their current profits (↑ current profits = ↑ potential × efficiency) and the profits they could obtain in the future (↑ unattained potential = ↑ potential x [1 - efficiency]). The map in **Error! Reference source not found.** shows the increase in current profits, while the map in **Error! Reference source not found.** shows the increase in unattained potential. In this case, the gains in current profits an unattained potential are more evenly spread out through the three regions of the country.

# 5 CONCLUDING REMARKS

In this study, we develop a spatial and economic tool for strategic analysis and visioning to help understand where the best opportunities for investments in agriculture, with specific examples for investments in irrigation and roads in Ethiopia and Malawi. For such investments to be effective for poverty alleviation, it is necessary that they lead to farm-level increases in productivity and are translated into higher incomes and better livelihoods for rural households. Our proposed approach utilizes stochastic frontier analysis (SFA) to estimate smallholders' agricultural potential under optimal conditions and compare it with their current performance to assess their efficiency levels. SFA allows the econometric exploration of the notion that, given fixed local agroecological and economic conditions in a region and the occurrence of random shocks that affect agricultural production, the decisions farmers and policymakers make translate into higher or lower production and profits. Inefficiency is then defined as the loss incurred by operating away from an ideal production frontier, and by estimating where this frontier lies, and how far each producer is from it, SFA helps to identify local potential and efficiency levels to construct the typology.

We use our typology results to assess where investments in agriculture would be more effective in bringing rural households out of poverty (closing the poverty gap), and how two different types of investments can increase rural households' incomes through an increase in the profitability of smallholder agriculture. The first scenario looks at the impact of an increase in access to irrigation through river diversion methods, while the second scenario looks at the impact of an increase in market access, which we simulate by analyzing what would be the impact of reducing travel time to the nearest market (city of least 25,000 inhabitants) from any farm in the country by 50%.

For Ethiopia, we find pockets of considerable unattained farm profits located throughout the central and western parts of the country, where opportunities for investments to close efficiency gaps in agricultural production and marketing can yield high returns. Low potential in the eastern lowlands limit opportunities for gains from efficiency-oriented investments, and development efforts in these regions should be focused in long-term, large scale interventions that shift the agricultural frontier. With respect to poverty alleviation, our results show that for many regions in the country, especially in the high central plateau, investing in increasing the efficiency of smallholders would be enough to close the poverty gap. In contrast, many areas in the Somali, Tigray, Afar, Oromia, and SNNP regions would require unrealistically high shifts in their agricultural potential due to its current low level combined in many cases with higher than average poverty gaps. The results from the improved irrigation access scenario are heavily constrained by the surface water availability constraint and show that the largest impacts would be observed in Somali and Afar, while in the case of the improved market access scenario, these benefits would extend to Tigray as well.

For Malawi, our maps show higher agricultural potential in the Northern and Central regions of the country, consistent with 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). The southern region suffers from lower potential due to poorer general weather conditions and lower rainfall levels. The unattained potential map shows that despite 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 investments in those areas as well. The poverty analysis shows that the incidence and depth of poverty are higher in the Southern Region of Malawi, but that the poverty gap in all districts of the country could be closed by investing in efficiency enhancing interventions in agriculture without depending on investments that shift the agricultural profit frontier. The results from the improved irrigation access scenario show a larger impact in the Central Region of the country, particularly the districts of Kasungu, Dowa, and Salima, while the improved market access scenario benefits are more evenly spread out across the country.

## ABOUT THE AUTHORS

Eduardo Maruyama is a Research Coordinator and Phoebe Scollard is a Senior Research Analyst in the Markets, Trade, and Institutions Division at IFPRI.

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## APPENDIX

## Table 5: Ethiopia: ESS3 summary statistics (prices and land use)

| | Estimation sample | | Rest of ag. sample | | T-test | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev. | Mean | Std. Dev. | Difference | |
| **Crop prices (Birr)** | | | | | | |
| **Maize** | 3.89 | 0.92 | 4.15 | 0.96 | -0.25 | *** |
| **Sorghum** | 4.83 | 1.36 | 5.26 | 1.35 | -0.44 | *** |
| **Teff** | 17.01 | 54.73 | 13.74 | 25.86 | 3.27 | ** |
| **Wheat** | 7.63 | 0.65 | 7.56 | 0.80 | 0.07 | *** |
| **Sesame** | 13.69 | 2.42 | 13.60 | 2.51 | 0.09 | |
| **Banana** | 3.71 | 3.86 | 4.18 | 4.34 | -0.47 | *** |
| **Chat** | 107.57 | 123.62 | 97.73 | 78.87 | 9.84 | *** |
| **Coffee** | 26.67 | 26.57 | 25.33 | 19.58 | 1.34 | |
| **Fertilizer prices (Birr)** | | | | | | |
| **Urea** | 11.16 | 3.03 | 13.44 | 34.96 | -2.28 | ** |
| **DAP** | 14.53 | 3.20 | 14.13 | 1.96 | 0.40 | *** |
| **NPS** | 14.63 | 3.01 | 13.97 | 2.98 | 0.66 | *** |
| **Seed prices (Birr)** | | | | | | |
| **Improved maize** | 8.63 | 4.80 | 8.99 | 6.25 | -0.36 | * |
| **Traditional maize** | 31.10 | 55.83 | 39.08 | 148.22 | -7.99 | * |
| **Sorghum** | 8.24 | 2.75 | 9.02 | 3.04 | -0.79 | *** |
| **Teff** | 14.15 | 1.29 | 14.25 | 1.46 | -0.10 | * |
| **Wheat** | 10.95 | 1.54 | 10.46 | 1.47 | 0.49 | *** |
| **Barley** | 7.97 | 1.37 | 8.27 | 1.58 | -0.30 | *** |
| **Horse beans** | 15.44 | 1.52 | 16.12 | 2.57 | -0.67 | *** |
| **Wages (Birr)** | | | | | | |
| **Men** | 59.33 | 74.37 | 70.92 | 89.65 | -11.60 | *** |
| **Women** | 30.90 | 14.49 | 35.86 | 17.64 | -4.96 | *** |
| **Children** | 12.98 | 5.68 | 14.22 | 6.39 | -1.24 | *** |
| **Landuse type (%)** | | | | | | |
| **Evergreen forest** | 0.06 | 0.16 | 0.03 | 0.13 | 0.03 | *** |
| **Closed shrublands** | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | * |
| **Open shrublands** | 0.04 | 0.13 | 0.10 | 0.23 | -0.05 | *** |
| **Woody savanna** | 0.12 | 0.18 | 0.10 | 0.20 | 0.02 | ** |
| **Savanna** | 0.14 | 0.25 | 0.16 | 0.28 | -0.03 | *** |
| **Grasslands** | 0.13 | 0.19 | 0.11 | 0.18 | 0.02 | *** |

| | | | | | | |
|---|---|---|---|---|---|---|
| Croplands | 0.21 | 0.24 | 0.24 | 0.26 | -0.04 | *** |
| Croplands / natural vegetation mosaic | 0.30 | 0.26 | 0.25 | 0.24 | 0.05 | *** |
| Urban, wetlands, or barren | 0.00 | 0.01 | 0.00 | 0.01 | 0.00 | |
| Observations | | 1216 | | 1839 | | |

## Table 6: Malawi: IHS4 summary statistics (prices and land use)

| | Estimation sample | | Rest of ag. sample | | T-test | |
|---|---|---|---|---|---|---|
| | Mean | Std. Dev | Mean | Std. Dev | Difference | |
| **Crop prices (MWK)** | | | | | | |
| Maize | 151.16 | 30.92 | 149.57 | 29.93 | 1.59 | ** |
| Tobacco | 404.36 | 185.22 | 397.08 | 184.24 | 7.28 | * |
| Groundnuts | 228.57 | 63.90 | 231.78 | 61.60 | -3.21 | ** |
| Beans | 460.54 | 102.93 | 473.21 | 107.46 | -12.67 | *** |
| Soy | 250.75 | 48.20 | 266.45 | 41.03 | -15.69 | *** |
| Pigeon peas | 313.09 | 47.62 | 313.87 | 51.62 | -0.78 | |
| Rice | 328.11 | 62.14 | 308.20 | 69.38 | 19.91 | *** |
| **Fertilizer prices (MWK)** | | | | | | |
| Chitowe | 382.36 | 42.38 | 378.89 | 42.45 | 3.47 | *** |
| Urea | 357.71 | 40.69 | 354.64 | 41.16 | 3.08 | *** |
| **Seed prices (MWK)** | | | | | | |
| Maize | 588.63 | 290.19 | 550.59 | 293.53 | 38.04 | *** |
| Groundnuts | 494.62 | 145.57 | 537.01 | 152.51 | -42.39 | *** |
| Beans | 635.91 | 112.06 | 642.19 | 119.15 | -6.29 | ** |
| Soy | 378.24 | 69.96 | 391.67 | 60.84 | -13.43 | *** |
| Pigeon peas | 567.88 | 141.64 | 516.36 | 152.69 | 51.52 | *** |
| **Wages (MWK)** | | | | | | |
| Men | 918.94 | 362.54 | 922.53 | 363.77 | -3.58 | |
| Women | 749.49 | 222.72 | 753.41 | 226.64 | -3.92 | |
| **Landuse Type** | | | | | | |
| Forest and closed shrubland | 0.01 | 0.08 | 0.01 | 0.09 | 0.00 | |
| Woody savanna | 0.08 | 0.27 | 0.07 | 0.25 | 0.01 | ** |
| Savanna, grasslands, sparse vegetation | 0.74 | 0.44 | 0.74 | 0.44 | 0.00 | |

| | | | | | | |
|---|---|---|---|---|---|---|
| Urban and wetlands | 0.01 | 0.08 | 0.01 | 0.12 | -0.01 | *** |
| Croplands | 0.02 | 0.13 | 0.02 | 0.13 | 0.00 | |
| Croplands / natural vegetation mosaic | 0.15 | 0.36 | 0.15 | 0.36 | 0.00 | |
| **Observations** | | 3,264 | | 6,431 | | |



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