Targeting investments in roads, small-scale irrigation and rural electrification in Senegal

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Abstract

Investments in roads, irrigation and electrification are often favoured by governments and donors as promising means for accelerating economic growth and poverty reduction in rural areas. In this study, we develop a spatial and economic tool for strategic analysis and visioning to help identify the best opportunities for rural infrastructure investments in Senegal. The methodology relies on the stochastic frontier analysis (SFA) to (i) identify areas of high agricultural potential with low accessibility to prioritize investments in road infrastructure according to a spatial model that estimates the minimum time taken to travel from any point in a country to the nearest market, and (ii) estimate average household gains in agricultural efficiency by comparing smallholders' performance under current conditions and under a scenario of improved access to small-scale irrigation and rural electrification. Our results show that the largest concentration of high agricultural potential areas for cereals is located in the region of Saint-Louis in the north, specifically in the departments of Dagana and Podor. In the case of horticulture, the areas with higher potential are in Rufisque, Thies and Tivaouane, and to a lesser extent Dagana. For the rice producers' sample, the divide in the distribution of potential is very clear with medium to high potential in the Senegal River Valley (north) and medium to low potential in the Anambe Basin (south). In addition, results show that farms in Podor (Saint-Louis) are among the best targets for investments in small-scale irrigation given their high potential and low efficiency levels. In the case of profit gains from investments in rural electrification, it is observed that while the entire area covered by rice would benefit from electrification, higher profits are expected in the departments of Saint-Louis and Dagana, Bakel and across the Anambe Basin.

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

JEL codes: D24, O13, O18, Q18, R11, R12

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1. Introduction

In Senegal, agriculture is one of the key sectors of the economy. With more than half of its active population employed in the sector, agriculture plays an essential social and economic role by ensuring the livelihood of thousands of households. These family farms often combine cash crops and subsistence food crops, while owning a few animals in extensive or semi-intensive breeding. Agriculture accounted for an average of 18.8 percent of the gross domestic product (GDP) over the period between 1960 and 2017 (World Bank, 2019). Yet, Senegal relies heavily on imports to complement local production to meet food demand, and several programs have been put in place in the last two decades to reduce this dependency and increase the country's food self-sufficiency.[1] While some of these policies have been effective in increasing local production and reducing the heavy dependence on food imports,[2] significant investments are still needed in the agricultural sector to meet national demand and consumers' preferences, challenges that will keep growing given current population and urbanization trends.

We hypothesize that for investments in roads, irrigation, and electrification 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. Therefore, 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 roads, small-scale irrigation and rural electrification are in Senegal.

To prioritize areas for investments in road infrastructure, we identify areas of high agricultural potential with low accessibility according to a spatial model that estimates the minimum time taken to travel from any point in a country to the nearest market. For irrigation investments, we use a spatial analysis model parametrized to approximate situations in which the adoption of the main smallholder irrigation technologies (i.e., pumps and small reservoirs) can be accommodated to identify which areas are most suitable for small-scale irrigation. For electrification investments, we use a Heckman selection model to predict what would be the consumption of electricity for unconnected rural households under universal access. We then estimate agricultural potential and efficiency estimates for smallholders using SFA under different scenarios of expansion of small-scale irrigation and rural electrification infrastructure.

The rest of the paper is organized as follows. After the first section devoted to the introduction, Section 2 describes the state and role of the road, irrigation and electricity infrastructure in Senegal's economy. Section 3 describes the methodology used for the analysis and the data source. In Section 4 the findings are presented. The final section is devoted to the conclusion.

[1] For instance, policies including the Grand Agricultural Offensive for Food and Abundance (GOANA) and the accelerated Program for Agriculture in Senegal (PRACAS) have attempted to reduce rice imports by increasing local production through input subsidies (seeds and fertilizers) and investments in irrigation infrastructure, while different trade policies have restricted the imports of onions, potatoes, and carrots.
[2] For example, 63 percent of the rice consumed in Senegal in 2017 was produced locally (DPEE, 2018).

2. Context of the study

In Senegal, infrastructures including roads, irrigation, and electrification, are crucial for the economic and social development of the country. Despite, the country access to sea, the road network plays an important role to ensure connectivity for transport and trade. Senegal's main road corridor runs from Dakar to Bamako, bordering Mauritania, and is one of the main international trade corridors in the subregion. The existing road network provides adequate connectivity at the regional, national and international levels that has prioritized connecting Dakar and other large cities to major ports, provincial capitals and smaller cities (Torres, et al., 2011). The geographic concentration of Senegal's population along the coast makes it a challenge to improve connectivity for rural areas where only 29 percent of the population lives within two kilometers of an all-weather road (Gwilliam, et al., 2008). Extending the rural road network remains a strong priority for the Senegalese government to raise cash income from agricultural sales in Senegal, along with agriculture yield, high-value crops and direct selling to the market (Torres et al., 2011).

Irrigated land in Senegal accounts for only two percent of the total cultivable land (PARIIS, 2016). With high spatial variation in rainfall patterns[3] and the constant risk of drought, irrigation can play an important role in increasing agricultural productivity and building up smallholders' resilience. Since the 2008 food crisis, public interventions targeting irrigated crops have resurged, such as the GOANA (rice) and PRACAS (rice and off-season fruits and vegetables) projects.[4] However, despite these private and public initiatives, the potential for irrigation is still far from being attained. FAO (2016) estimates that Senegal's potential irrigable land amounts to 350,000 hectares, 30 percent of which is not yet irrigated. Land area equipped for irrigation is estimated to be around 105,000 hectares, with 75,600 hectares in the Senegal River Valley, 15,000 hectares exempt of saline intrusion in the Casamance, 10,000 hectares in the Niayes, 3,580 hectares in the Anambe Valley, and 600 hectares in the Senegal Orientale and the Peanut Basin. Hence, there is still plenty of potential for increasing agricultural productivity through small-scale irrigation expansion in Senegal. However, this should be carefully guided to ensure that limited resources are used efficiently, maximizing the impact of small-scale irrigation considering biophysical and economic constraints and opportunities in Senegal.

The Government of Senegal aims to achieve universal access to power by 2025[5] through a combination of on- and off-grid solutions, but the country's rural concessions program faces significant hurdles. Priorities include lowering the cost of generation by reducing dependence on imported liquid fuels and increasing electricity access – particularly in rural areas. Rural households have low levels of electricity consumption and a limited ability to pay, in comparison to the high cost of extending the grid to those

[3] Mean annual rainfall is around 250 mm in the north and 1200 mm in the south (FAO, 2016).

[4] Other recent initiatives include: (i) PAPIL (Projet d'Appui à la Petite Irrigation Locale), aimed at reducing poverty and food insecurity through the promotion of irrigation infrastructure and climate change adaptation measures in the regions of Fatick, Kolda, Tambacounda, and Kedougou; (ii) PASA (Projet d'Appui à la Sécurité Alimentaire) LouMaKaf, aimed at improving food security and incomes through access to infrastructure, especially for water management, storage, and access to adapted technologies and services in the regions of Louga, Matam and Kaffrine; and (iii) PARIIS, the Sahel incentive project of the World Bank that aims at increasing the irrigated area in six countries of the Sahel including Senegal during the period 2018-2020 (PARIIS, 2016; FAO, 2016).

[5] The current access rate is 64 percent, 43.5 percent in rural areas and 90 percent in urban areas (Power Africa, 2020a)

areas and the constraints imposed by the seasonality of power demand for agriculture (Banerjee et al., 2017; Blimpo et al., 2019). Also, when electricity is provided in rural areas, evidence from Kenya (Jacobson, 2007) and Senegal (ESMAP, 2008) indicates that initial access was mainly dedicated to illumination, radio and television, with limited utilization in agriculture or other economic activities. Yet, access to electricity can improve socioeconomic conditions in developing countries by affecting positively key factors of development: poverty, health, education, income and the environment (Torero, 2015). In rural areas where agriculture is the main economic activity lack of access to electrification is one of the major barriers to economic development. Smallholder farmers in rural areas would benefit from electricity in multiple ways, especially those involved in power intensive value chains.

3. Methodology and data source

3.1 Empirical strategy

Our proposed methodology assumes that for investments in rural infrastructure to be effective for poverty alleviation, they need to lead to farm-level increases in productivity and be translated into higher incomes and better livelihoods for rural households. Therefore, we utilize stochastic frontier analysis (SFA) to (i) identify areas of high agricultural potential with low accessibility to prioritize investments in road infrastructure according to a spatial model that estimates the minimum time taken to travel from any point in a country to the nearest market, and (ii) estimate average household gains in agricultural efficiency by comparing smallholders' performance under current conditions and under scenarios of improved access to small-scale irrigation and rural electrification. While similar, the methodologies for small-scale irrigation and electrification differ slightly from each other due to the intrinsic differences in how these services are provided. In the case of electricity, once the provider has expanded the grid close enough for users to connect to it, consumption is limited only by the cost of the service bill. For small-scale irrigation, while farmers need to invest in equipment such as motor or solar pumps, and cover some running costs (fuel, maintenance, etc.), biophysical factors such as the availability of adequate water sources (surface or groundwater) and the topography (slope) of the land can be insurmountable barriers regardless of the availability of funds. Hence, for the small-scale irrigation SFA estimation it is crucial to include the impact of the biophysical constraints on agricultural potential, while for the electrification SFA estimation, it is essential to make an adequate prediction of electricity consumption for currently unconnected households or regions.

The methodology for the small-scale irrigation analysis is illustrated in Figure 1. We use GIS measures for access to water sources (surface and groundwater) and slope, and the distance to agricultural markets (purple box) to capture the biophysical and economic constraints to small-scale irrigation and its impact on agricultural potential and efficiency through the SFA estimation (green box). We then simulate the impact of increasing access to small-scale irrigation, within the biophysical constraints established by the GIS variables on smallholder profits across the country (red box).

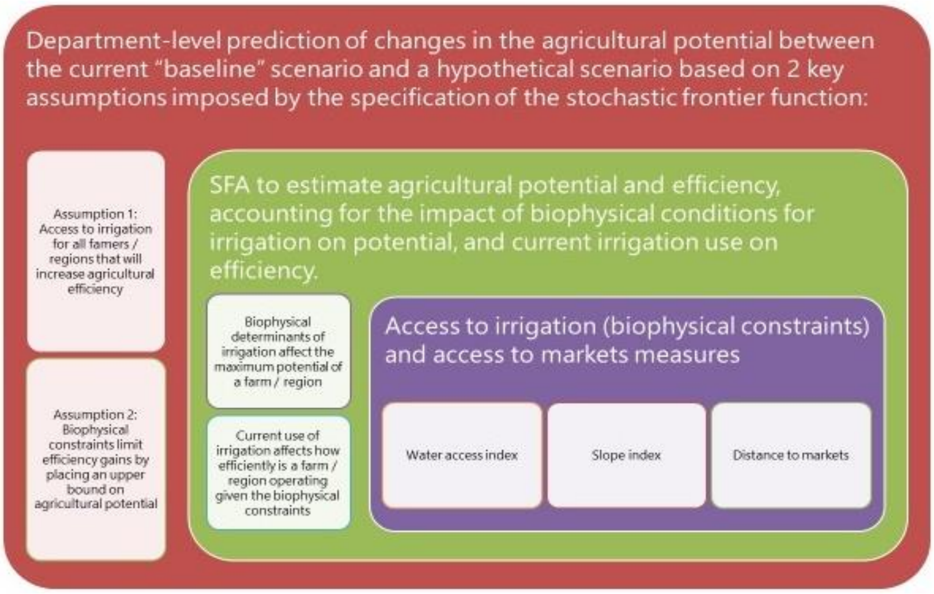

Figure 1. Methodological approach for small-scale irrigation analysis

Source: Own elaboration

The methodological approach for the electrification analysis is illustrated in Figure 2. The first step (in the yellow box) involves using a Heckman selection model (Heckman, 1976) to predict what would be the consumption of electricity for unconnected rural households under universal access. In the second step we estimate agricultural potential and efficiency estimates for smallholders using SFA under the assumption that electricity helps reduce the farms' efficiency gap. This allows us to compare estimated efficiency levels under current conditions and under universal access (using the predicted electricity consumption from the first step) and calculate what are the agricultural revenue gains from electrification. In the third step we extrapolate these results for the whole country and combine them with GIS information on the status of Senegal's electrical grid and connectivity.

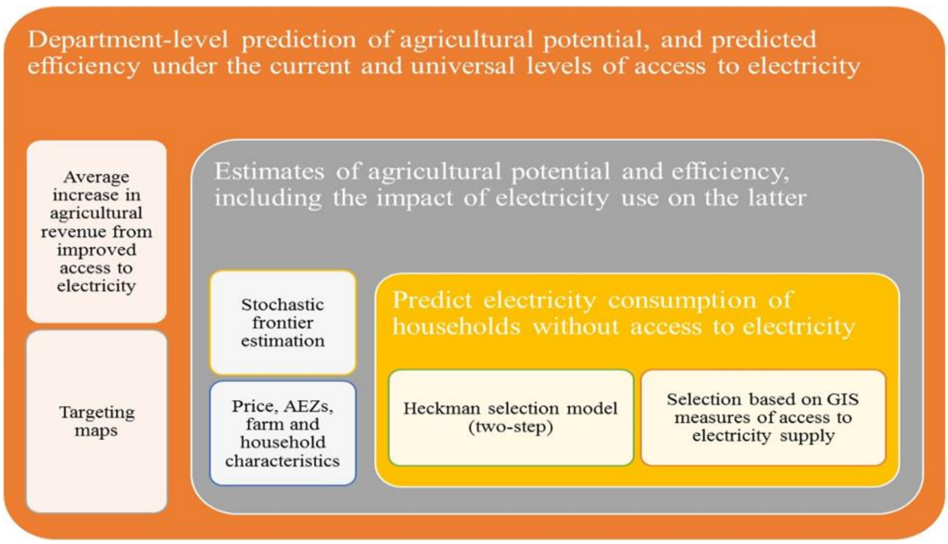

Figure 2. Methodological approach for electrification analysis

Source: Own elaboration

These approaches allow us to identify areas where improved access to markets could yield high returns for smallholders and compare estimated efficiency levels under current conditions and hypothetical scenarios of improved access to small-scale irrigation and electricity to assess the agricultural revenue gains linked to each case. Finally, we extrapolate these results for the whole country and combine them with GIS information on small-scale irrigation suitability, the countries' electrical grid and connectivity rates. Our analytical results and maps highlight the spatial heterogeneity in opportunities and priorities for roads, small-scale irrigation and electrification investments in Senegal.

A more detailed description of the methodology is provided in the Annex.

3.2 Data source

The PAPA project collected data from rural households across Senegal, segmenting the total study sample into three sub-samples: dry cereals producers in all departments of the country except for the urban departments of Dakar, Pikine, and Guediawaye; horticulture producers in the Niayes area (regions of Dakar, Thies, Louga, and Saint-Louis) and the Delta of the Senegal River Valley (Dagana and Podor); and irrigated rice producers in the Senegal River Valley and the Anambe Basin. While the survey instruments administered to each of these subsamples share several modules, each subsample was selected following a different sampling strategy, and responded to a specific agricultural module designed to better fit their farming system.

A two-stage sampling technique was used to draw the samples for the three surveys. The dry cereals producers' survey sample was drawn from the DAPSA (Direction of Analysis, Forecasting and Agricultural Statistics) database[6] with census districts (CDs) as primary units and farm households as secondary units, proportionally to farm size. The sample is distributed across the 42 agricultural departments of Senegal (i.e., all departments in the country minus the urban departments of Dakar, Pikine and Guediawaye). The data collection took place between April and May 2017 and includes 4,480 producers representing all dry cereal producing households in Senegal.

The horticulture sample was drawn from the Direction of Horticulture 2012 producer census for the Niayes area, and from the ISRA-BAME Middle Scale Farmers Project (MSF) and SAED databases for the Senegal River Valley, stratified by horticultural production sites or villages in the first stage, for a total sample of 1,305 households. The data collection took place between May and June 2017.

The irrigated rice producers' sample was drawn from the SAED database for the Senegal River Valley and the FEPROBA (Federation of Producers of the Anambé Basin) for the Anambé Basin, with economic interest groups (EIGs) as the primary sampling unit, and farm households as the secondary units, for a total of 730 households. The data collection took place between July and August 2017.

[6] This database is used by DAPSA to conduct annual surveys on dry cereals producers and is sampled from the 2013 General Population, Housing, Agriculture and Livestock Census (RGPHAE, *Recensement Général de la Population, de l'Habitat, de l'Agroiculture et de l'Élevage*).

4. Results and Discussions

4.1 Descriptive analysis

4.1.1 Crop production and sales

The main crops cultivated by producers in the dry cereals sample are peanut and millet, cultivated by more than 60 percent of the sample, followed by maize, cowpeas, rice and sorghum, produced by more than 15 percent of the sample (Table 1). The lack of horticultural production can be explained by the dry cereals' survey coverage area that targets rainfed regions where off-season horticultural production is minor due to climatic conditions and limited access to irrigation. Table 1 also shows that in rainfed areas peanut is the main market crop (sold by around 47 percent of the sample) while cereal crops are hardly commercialized and mainly used for household consumption.

Table 1. Senegal PAPA Survey: Dry cereals survey crops

Crops	% of producers cultivating	% of producers selling
Peanuts	69.8	46.6
Millet	60.7	7.2
Maize	34.6	3.7
Cowpea	22.2	6.4
Rice	19.0	1.7
Sorghum	16.6	1.6
Watermelon	2.5	2.1
Sesame	2.1	1.8
Total Producers	4,480	4,480

Note: Percentages out of households that planted at least one crop throughout the year. No. producers = 4,480.
Source: Projet d'Appui aux Politiques Agricoles (2017)

Table 2 shows the main crops produced in the horticulture sample, with onion (the most consumed vegetable in the country) being by far the most frequently produced crop followed by cabbage, tomato, chili pepper and rice.[7] The table also shows that unlike cereal crops, most horticulture crops are market-oriented.

Table 2. Senegal PAPA Survey: Horticulture survey crops

Crops	% of producers cultivating	% of producers selling
Onion	64.7	64.3
Cabbage	28.3	28.3
Tomato	26.3	26.2
Chili Pepper	13.0	13.0
Rice	11.9	7.3
African eggplant	9.4	9.3
Eggplant	9.1	9.1
Potato	8.7	8.7
Carrot	8.1	8.1

Note: Percentages out of households that planted at least one crop throughout the year. No. producers = 1,292.
Source: Projet d'Appui aux Politiques Agricoles (2017)

[7] The presence of rice in the horticulture survey is explained by the diversity of farming systems in the Senegal River Valley.

Regarding the irrigated rice survey, Table 3 shows that rice producers also cultivated leguminous crops (such as peanut) and cereals (such as maize). Apart from these, other crops (not reported here) are cultivated by less than five percent of the sample.

Table 3. Senegal PAPA Survey: Irrigated rice survey crops

Crops	% of producers cultivating	% of producers selling
Rice	86.4	52.9
Maize	23.3	17.3
Peanuts	17.9	15.3

Note: Percentages out of households that planted at least one crop throughout the year. No. producers = 730.
Source: Projet d'Appui aux Politiques Agricoles (2017)

4.1.2 Farm characteristics

Table 4 shows some key characteristics of the farmers in each sample. In the three farming systems, farm households are headed on average by older men in their early fifties, reflecting the lack of access to productive resources, particularly land, for women and the youth. On average households are composed of 8-10 members and the average cultivated area is around six hectares for dry cereal-producing farms and three hectares for irrigated rice farms.

Table 4. Senegal PAPA survey: Farm characteristics

	Mean value for the three samples*		
	Cereals	**Irrigated rice**	**Horticulture**
Farm Characteristics			
Male household head (%)	93.1 (25.3)	86.8 (33,91)	95.9 (19.8)
Age of household head	53.2 (13.4)	51.7 (12,1)	50.7 (13.3)
Household size	10.0 (5.5)	8.7 (4,54)	10.3 (4.9)
Cultivated area (hectares)	5.7 (8.2)	2.7 (7,34)	1,253.3 (9,863.5)
Irrigation (%)	4.8 (21.4)	82.3 (38,22)	92.1 (27.0)
Head Education (% of households)			
No formal education	62.5 (48,41)	57.3 (49,49)	22.0 (41.4)
Primary school	13.8 (34.46)	11.9(32.46)	11.72 (32.18)
Middle School	7.59 (26.48)	NA	NA
Secondary school or higher	3.49 (18.34)	6.43 (24.54)	63.98 (48.02)
Alphabetization	12.6 (33,23)	18.8 (39,07)	2.3 (15.0)
Revenue (x1000 FCFA)			
Crop revenue	185.1 (555, 11)	658 (4,707)	4,398.4(57,448.0)
Livestock and byproduct	76.9 (386, 61)	145.6(1,297)	53.4 (277,45)
Non-agricultural revenue	87.7 (300, 90)	64.4 (250.8)	92.4 (385,64)
Transfer revenue	47.5 (345, 57)	61.0 (285.0)	59.5 (263,5)
Total non-crop revenue	212.1	270.9	205.2
Observations	4,533	778	1 305

Note: Estimates include all PAPA households not only those included in the estimation sample. Standard deviation in parentheses.
Source: Projet d'Appui aux Politiques Agricoles (2017)

The large difference in the use of irrigation among horticulture and rice producers (92 percent and 82 percent, respectively) versus cereal producers (5 percent) can be easily explained by the nature of the three farming systems: farmers in the cereal survey are in areas where rainfed agriculture is the dominant activity, while the rice survey purposely targeted irrigated rice producers and horticulture production in Senegal which is mainly irrigated. Other differences are the higher education levels and higher total crop revenue for the horticulture farmers (due to the market orientation of their production), and the importance of by-product revenues for rice farmers (e.g. sale of rice hulls).

4.1.3 Water access and slope measures

Since the PAPA survey households are geo-referenced, we can estimate their exact index value for the water access and slope measures described in Section 3.3. In the cereals and horticulture surveys estimation samples[8], 68 percent of households are in marginal or highly marginal areas. Thirty percent of horticulture households are located in highly suitable areas compared to only 4 percent of cereal producers. This contrasts with the rice survey where 63 percent of households are in highly suitable areas and only 13 percent are located in marginal or highly marginal locations. On the other hand, the three surveys show that most of their farms are located in areas with a suitable slope for irrigation, with 92 percent of households in the cereals questionnaire, 93 percent in the horticulture sample, and 99 percent of the rice sample households receiving a slope index value of 100.

4.2 Heckman selection model results for the irrigated rice sample

Results for the maximum likelihood estimation of equations (1) and (2) are shown in Table 5. We assume electricity consumption (measured by the household's reported electricity expenditure in the PAPA survey) is a function of some basic household characteristics (household head's education, age and gender, household size, and farm size), whereas the likelihood that a household has access to electricity (reports being connected to the grid) is a function of the grid infrastructure measured by the distance to medium voltage lines and night time luminosity index. As expected, living at a closer distance to medium voltage lines positively affects the likelihood of having access to electricity, and more educated households with larger landholdings tend to consume more electricity.

[8] The estimation samples consider only the observations from each survey that are included in the SFA estimation and meet the condition that the farmer has land and positive crop profits, where profits include the estimated value of production.

Table 5. Senegal irrigated rice sample: Access to and consumption of electricity (Heckman selection model)

Observations	460
Selected	41
Non-selected	419
Chi-square	25.33

Electricity Expenditure (FCFA)	*Coeff.*	*Std. Error*
Head education: alphabtisation	28,847.82	10,939.19***
Head education: primary	24,691.13	13,703.13*
Head education:Niveau secondaire et plus	55,281.35	25,510.69**
Head Age	550.30	376.84
Head Female	-3,792.74	18,405.07
Household Size	-2,029.82	1,324.95
Land	20,455.83	6,364.44***
Constant	56,638.95	29,975.99*
Connected		
Distance to Medium Voltage Line	-1.3×10^{-4}	4.0×10^{-5}***
Night Light	-0.015	0.032
Household Size	0.085	0.024***
Land	-0.377	0.095***
Head age	-0.009	0.009
Head Female	-0.641	0.400
Head education: alphabtisation	-0.107	0.258
Head education: primary	-0.232	0.344
Head education: Niveau moyen	-5.604	.
Head education:Niveau secondaire et plus	-0.382	0.499
Constant	-0.595	0.512

Source: Own elaboration

4.3 SFA estimations

Tables Table 6, Table 7 and **Fehler! Verweisquelle konnte nicht gefunden werden.** show the results of the stochastic frontier estimation for each of the PAPA survey crop samples. The deterministic portion of the agricultural profit frontier is a function of input and output prices specific to each sample, AEZs (*land use* variables), and the water and market accessibility measures. The factors influencing (the variance of) the non-negative component of the error term associated with farm efficiency are physical capital (land, assets, non-farm income), human capital (household size, household head characteristics), an indicator for whether the farm is currently under irrigation or not, and for the irrigated rice sample the household's expenditure on electricity. The estimated coefficients from the regression in this table are used to predict regional-level agricultural potential (capped by the level of access to water for irrigation) and efficiency (limited by the actual use of irrigation, and electricity for the irrigated rice sample). Hence, for households without irrigation or electricity the SFA estimation allows us to assess and map how much of the performance loss (in terms of farm profits) is due to the limited agricultural potential of the farm coming from the lack of access to water for small-scale irrigation, or from the efficiency loss due to the lack of investments to tap into the existing water resources or connect to the electricity grid. Or, in other words, the analysis identifies how much more profitable agriculture could be in a region by investing in small-scale irrigation projects and rural electrification that would allow local farmers to benefit from their untapped potential.

Table 6. Senegal dry cereals sample: Irrigation SFA estimation

ln(Cereals Profits)	Coeff.	Std. Error
Crop Prices		
Millet	0.542	0.579
Maize	-0.284	0.832
Sorghum	0.792	0.488
Rice	-0.741	0.325**
Cowpea	-0.105	0.407
Peanut	0.655	0.230***
Sesame	0.017	0.428
Seed Prices		
Millet	-0.322	0.147**
Maize	0.014	0.285
Sorghum	- 0.166	0.526
Rice	0.944	0.255***
Cowpea	0.286	0.167*
Peanut	-0.125	0.104
Sesame	-0.841	0.523
Fertilizer Prices		
NPK	0.421	0.257
Urea	-0.094	0.245
Land Use		
Savanna	-0.605	0.203***
Wetland / Floodplain	-1.197	0.282***
Steppe	-0.471	0.397
Mangrove	-1.334	0.364***
Agriculture	-0.538	0.183***
Water bodies	-1.152	0.310***
Sandy area	0.326	0.329
Bare soil	-0.016	0.553
Settlements	-0.639	0.223***
Gallery and riparian forest	-0.704	0.347**
Agriculture in shallows and recessions	-0.854	0.288***
Woodland	-0.522	0.408
Irrigation and Accessibility		
Water access index	0.002	0.002
Slope index	0.002	0.004
Market access	0.043	0.034
Constant	8.449	0.832***
$ln\sigma_v$		
Constant	0.005	0.095
$ln\sigma_u^2$		
Uses irrigation	-0.796	0.330**
Family labor	-0.046	0.022**
Hired labor	-0.047	0.079
Land (ha)	-0.282	0.068***
log Asset expenses	-0.063	0.029**
Head polygamous	0.120	0.156
Head female	0.107	0.186
Head education: alphabtisation	0.158	0.217
Head education: primary	0.040	0.190
Head education: Niveau moyen	0.185	0.228
Head education:Niveau secondaire et plus	0.062	0.307
Constant	2.027	0.181***
σ_v	1.002	0.048
N		2,347

Source: Own elaboration

Table 7. Senegal horticulture sample: Irrigation SFA estimation

ln(Horticulture Profits)	Coeff.	Std. Error
Crop Prices		
Cabbage	0.350	0.282
Onion	-0.514	0.552
Pepper	0.244	0.142*
Tomato	0.678	0.165***
Rice	0.598	0.835
Seed Prices		
Cabbage	-0.173	0.287
Onion	-0.248	0.177
Pepper	0.605	0.256**
Tomato	-0.280	0.085***
Rice	-1.446	0.865*
Fertilizer Prices		
NPK	-0.303	0.681
Urea	0.405	0.454
Organic	0.201	0.214
Phytosanitary Prices		
Insecticide	0.182	0.157
Fongicide	0.109	0.285
Herbicide	-0.066	0.174
Land Use		
Wetland / Floodplain	-0.342	0.304
Steppe	-0.197	0.161
Plantation	-0.130	0.132
Agriculture	-0.206	0.195
Water bodies	-0.433	0.375
Sandy area	-0.070	0.241
Bare soil	0.045	0.174
Settlements	-0.137	0.192
Irrigated agriculture	-0.221	0.312
Agriculture in shallows and recessions	0.217	0.126*
Open mine	-0.300	0.277
Irrigation and Accessibility		
Water access index	-0.0001	0.001
Slope index	-0.008	0.006
Market access	-0.059	0.041
Constant	8.339	1.734***
$ln\sigma_v$		
Constant	-0.015	0.280
$ln\sigma_u^2$		
Uses irrigation	-0.204	0.728
Family labor	-0.444	0.381
Hired labor	-0.554	0.354
Land (ha)	0.0003	0.0005
log Asset expenses	-0.077	0.107
Head polygamous	0.139	0.247
Head female	-0.213	0.337
Head education: alphabtisation	-1.687	2.866
Head education: primary	-0.277	0.369
Head education:Niveau secondaire et plus	0.149	0.258
Constant	1.617	0.752**
σ_v	0.992	0.139
N		1,079

Source: Own elaboration

Table 8. Senegal irrigated rice sample: Electrification SFA estimation

ln(Rice Revenue)	Coeff.	Std. Error
Crop Prices		
Maize	-2.268	0.690***
Rice	0.857	0.843
Peanut	1.217	1.678
Livestock Prices		
Cow	-0.610	0.422
Goat	0.522	0.983
Sheep	1.678	0.755**
Poultry	-0.244	0.822
Land Use		
Savanna	-0.093	0.530
Wetland / Floodplain	0.064	0.582
Steppe	-0.052	0.484
Agriculture	-0.299	0.413
Water bodies	0.775	0.281***
Settlements	0.196	0.439
Irrigated agriculture	-0.078	0.359
Woodland	-0.958	0.600
Irrigation and Accessibility		
Water access index	-0.002	0.003
Slope index	0.029	0.015**
Market access	0.063	0.056
Constant	-1.070	5.998
$ln\sigma_v$		
Constant	-0.067	0.424
$ln\sigma_u^2$		
log Electricity expenditure	-0.077	0.044*
Family labor	-0.075	0.039*
Hired labor	-0.450	0.162***
Land (ha)	-0.288	0.171*
log Asset expenses	-0.054	0.049
Head polygamous	0.277	0.262
Head female	0.337	0.372
Head education: alphabtisation	-0.369	0.263
Head education: primary	-0.063	0.357
Head education: Niveau moyen	0.016	0.375
Head education:Niveau secondaire et plus	-0.427	0.691
Constant	2.373	0.373***
σ_v	0.967	0.205
N		460

Source: Own elaboration

Because of the geographic clustering of each crop sample and lack of variation in the conditions for small-scale irrigation suitability within each of them, we see little impact of those variables on agricultural potential. Similarly, the extensive use of irrigation in the horticulture sample (92 percent in Table 4) prevents us from seeing much of an impact of irrigation on horticulture farmers, but we do observe a strong and significant effect of irrigation in reducing farm inefficiencies for cereals and rice producers.

The SFA estimation for the irrigated rice producers' sample in Table 8 includes the electricity expenditure variable as a factor affecting farm efficiency. The negative sign on the electricity expenditure variable indicates that an increase in electricity consumption is associated with a reduction in technical inefficiency. The estimated coefficients from the regression in this table are used to predict regional level agricultural potential and efficiency. When combined with the predicted electricity consumption for unconnected households obtained from the Heckman selection model estimation, the calculation gives us the potential and efficiency estimates for the universal access scenario.

4.4 Mapping results

4.4.1 Agricultural potential and efficiency

Dry cereals sample

Figure 3 shows the estimated agricultural potential from the dry cereals sample where agricultural potential is defined as the maximum possible profit[9] that a farmer can gain from crop production if operating at maximum efficiency. Areas with medium to high agricultural potential are concentrated in the agro-ecological zones located in the center-north (i.e., the sylvo-pastoral area of Linguere and Ranerou-Ferlo) and in the northern area (Dagana and Podor in the Senegal River Valley). Other areas with similar agricultural potential are located in the coastal Niayes area, in Bambey and Fatick in the Peanut Basin, and in Ziguinchor in Casamance. The remaining areas, mainly the eastern side of the country covering the regions of Tambacounda and Kedougou, show medium to low potential.

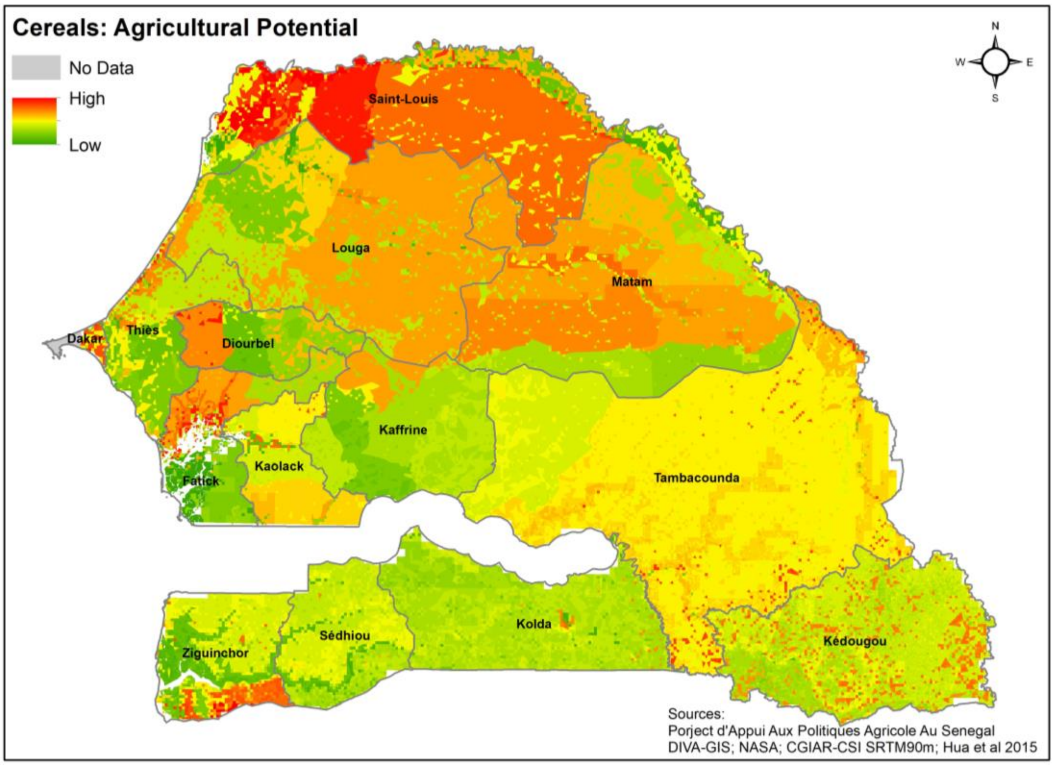

Figure 3. Dry cereals sample: Agricultural potential

[9] For this study, profits are defined as total revenues from crop and byproduct sales plus the value of own consumption minus the associated input costs.

The largest concentration of high potential areas is found in the region of Saint-Louis in the north, specifically in the departments of Dagana and Podor. Good access to surface water and proximity to agricultural markets and large urban areas (Saint-Louis) help explain this finding, despite generally low annual rainfall levels and land erosion and degradation issues. Other areas with high agricultural potential are Rufisque in the Dakar region, with immediate access to the capital and a shallow aquifer in the Niayes area, and Ziguinchor in the Casamance region, with the highest annual rainfall level in the country and better access to markets than neighbouring areas with similar agroecological conditions.

Figure 4 shows the estimated agricultural efficiency in the dry cereals sample, which measures the degree to which the potential in Figure 3 has or has not been attained. In combination, these two measures help identify the best spots for different types of interventions. In particular, investments in small-scale irrigation should be targeted to areas with medium to high agricultural potential due, in part, to good access to water sources, and medium to low efficiency where there is a significant efficiency gap to close.[10] These areas are mostly located in the departments of Dagana, Podor, Kanel, Ranerou-Ferlo, Matam, Kanel, Fatick, Bambey, Rufisque, Ziguinchor and Bakel.

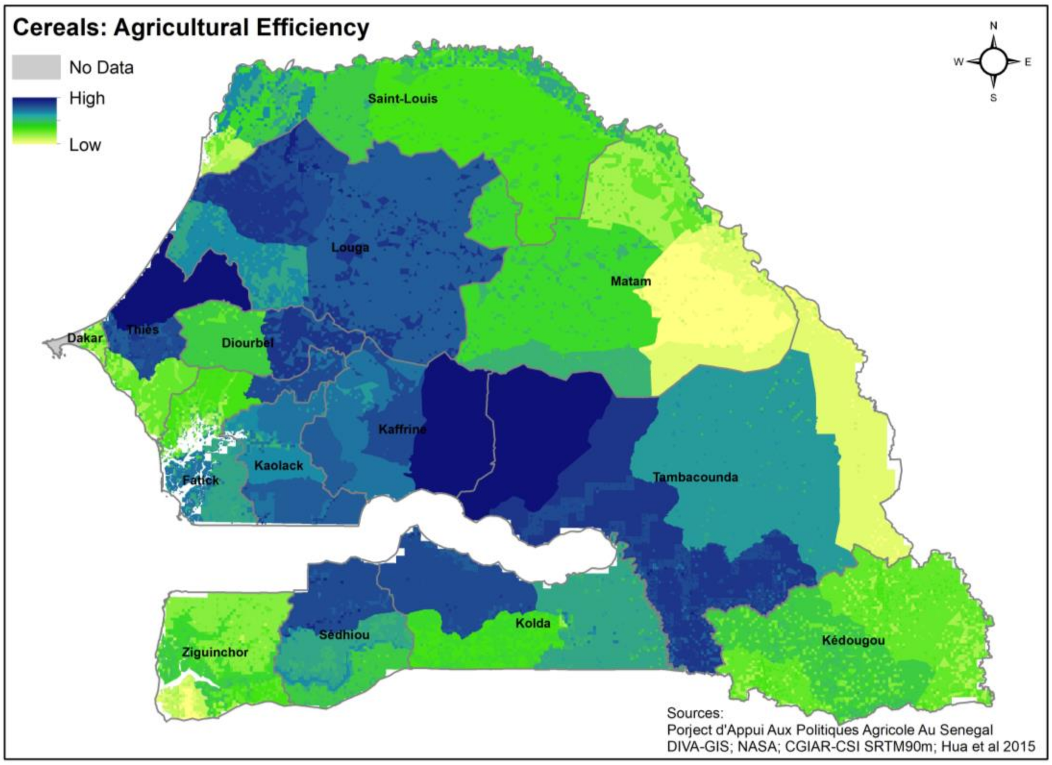

Figure 4. Senegal dry cereals sample: Agricultural efficiency

[10] Low agricultural potential areas would require longer term and larger investments that help shift the profit frontier beyond what small-scale irrigation projects could.

Horticulture sample

Figure 5 shows the estimated agricultural potential for the horticulture sample. Unlike the dry cereals sample, the horticulture region is spatially concentrated and less heterogeneous, with even and favourable access to surface or groundwater sources and agricultural markets. Areas with higher potential (Rufisque, Thies, and Tivaouane) benefit from their proximity to the largest cities in the country, Dakar and Thies. To a lesser extent, Dagana also shows considerable agricultural potential due to its proximity to Saint-Louis and the presence of processing industries that demand several crops such as tomatoes and rice.

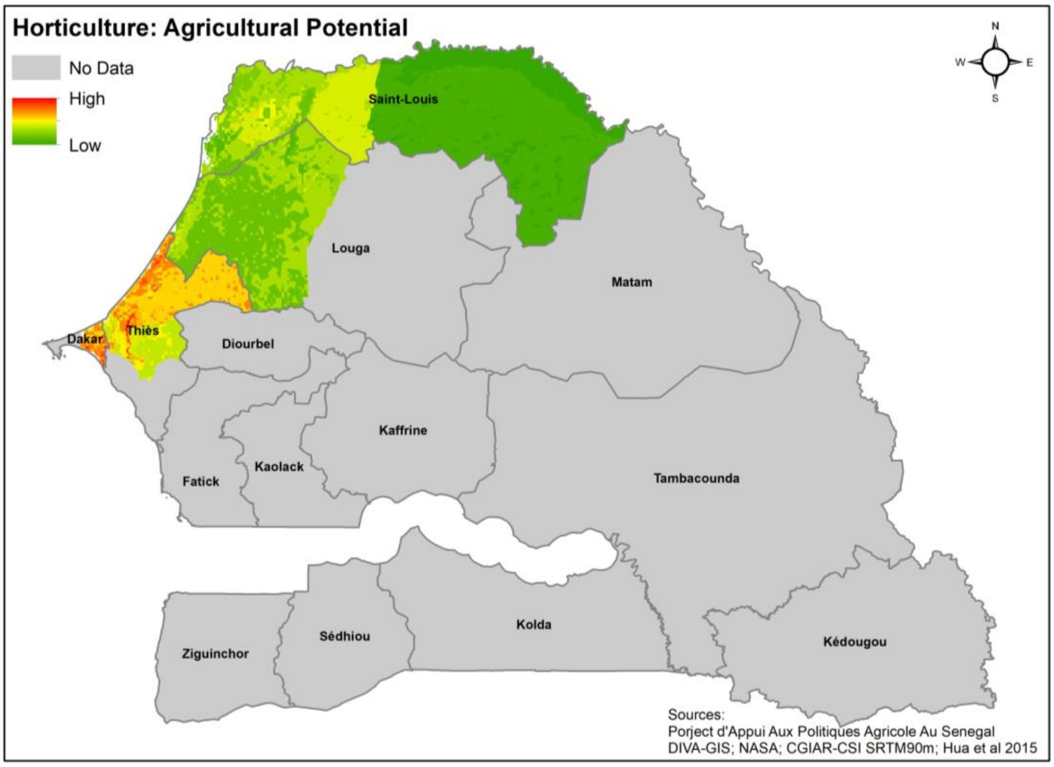

Figure 5. Senegal horticulture sample: Agricultural potential

Figure 6 shows the estimated agricultural efficiency for the horticulture sample. There are no evident areas to target with investments in small-scale irrigation investments in this sample given the high percentage of farmers already using irrigation among horticultural producers in this region, which is also reflected in the lack of areas with significant efficiency gaps (medium to high potential and medium to low efficiency) when combining figures Figure 5 and Figure 6.

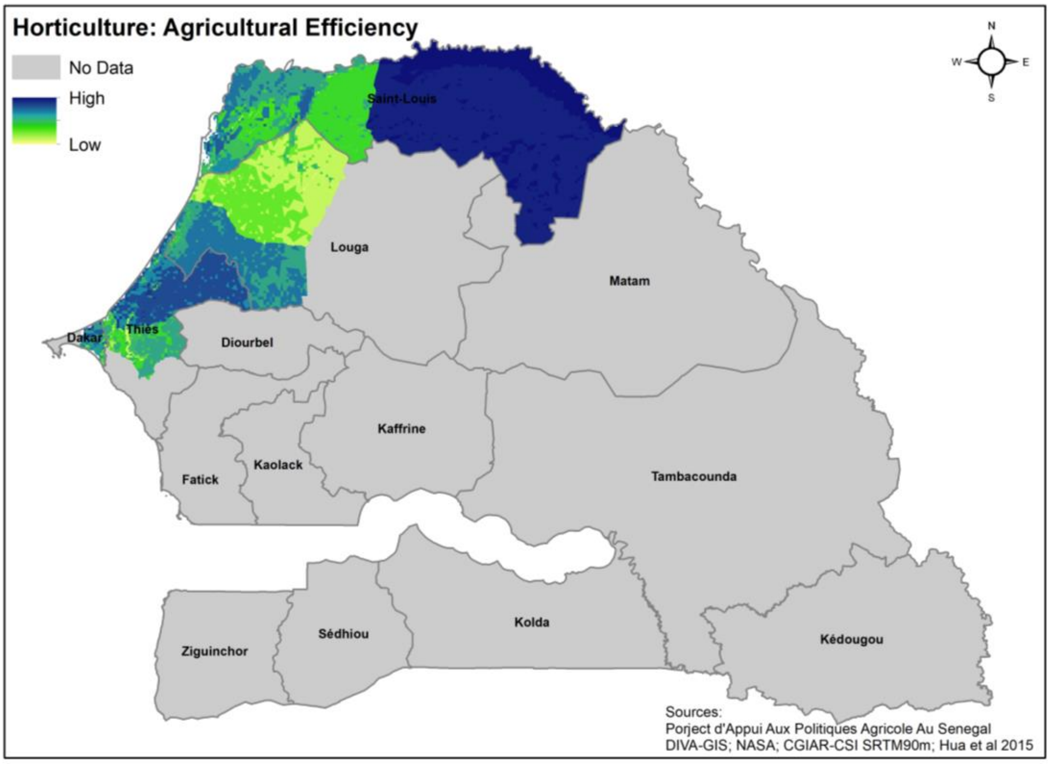

Figure 6. Senegal horticulture sample: Agricultural efficiency

Irrigated rice sample

Figure 7 shows the estimated agricultural potential for the irrigated rice sample. On average, the divide in the distribution of potential is very clear with medium to high potential in the Senegal River Valley (north), and medium to low potential in the Anambe Basin (south). This can be explained by better market accessibility in the Senegal River Valley and a longer history of government and donor support in the region. In combination with the agricultural efficiency estimates in Figure 8, these results show that farms in Podor (Saint-Louis) are among the best targets for investments in small-scale irrigation given their high potential and low efficiency levels.

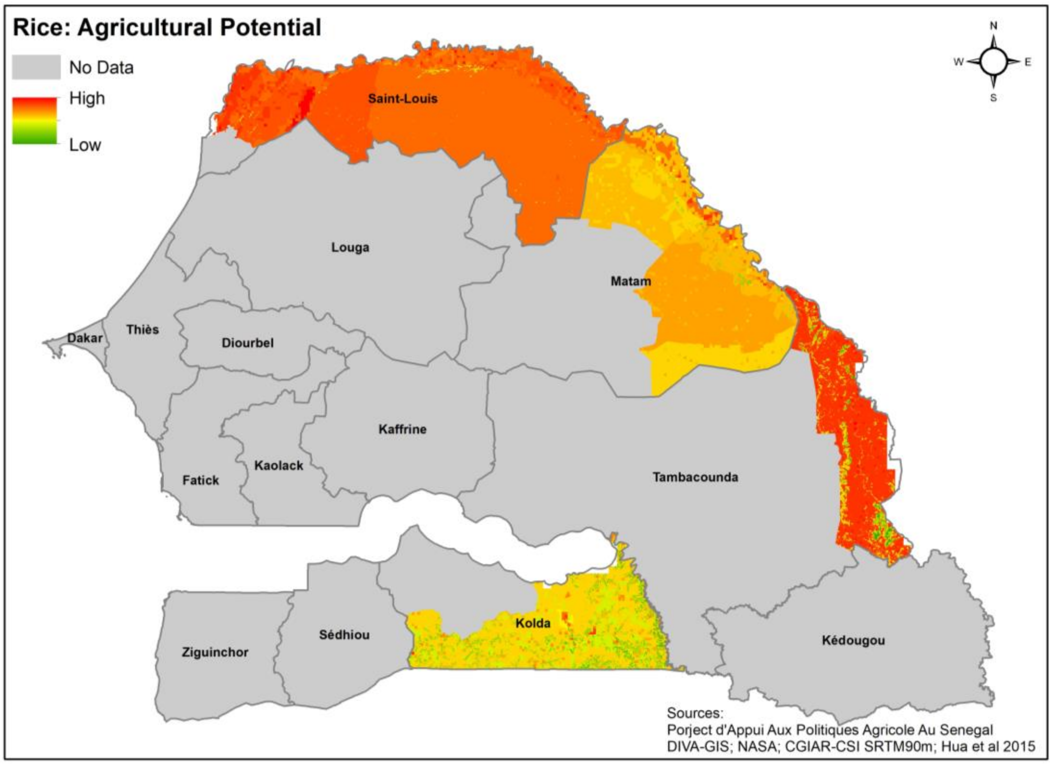

Figure 7. Senegal irrigated rice sample: Agricultural potential

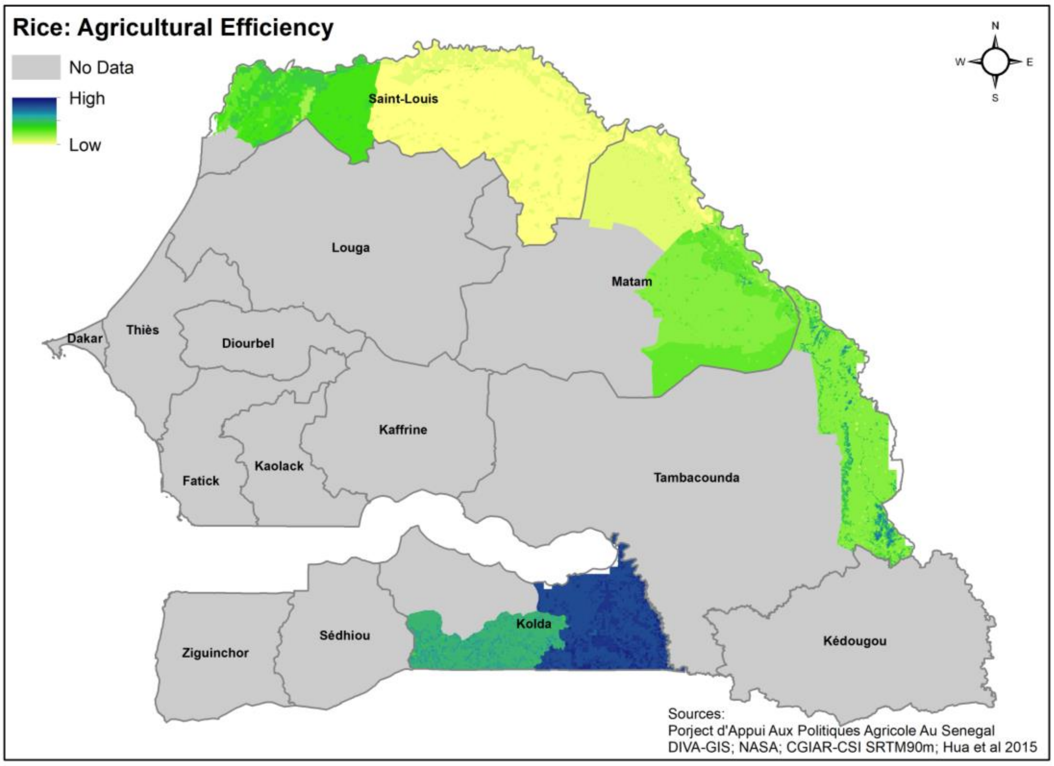

Figure 8. Senegal irrigated rice sample: Agricultural efficiency

4.4.2 Accessibility and road infrastructure

One of the factors influencing efficiency is the degree of market accessibility each region has. For this purpose, we have estimated the accessibility model described in Section 3.2 for Senegal (Figure 9) to determine what are the time costs of accessing the closest market, where *market* is defined as permanent agricultural markets, or as towns or cities with more than 25,000 inhabitants that can generate significant levels of demand for those products.

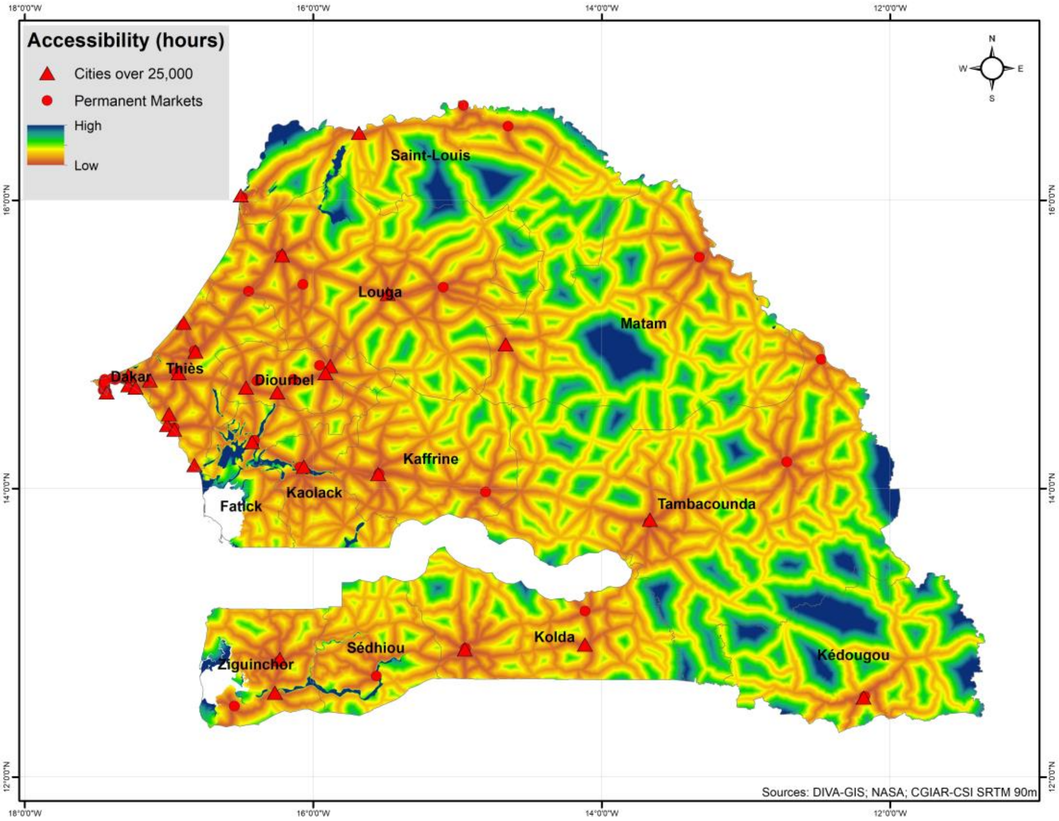

Figure 9. Senegal: Accessibility to permanent markets and cities with more than 25,000 inhabs.

The maps in Figures 10, 11 and 12 show the spatial patterns that result from superimposing the market access measure in Figure 9 with the attainable agricultural potential in each sample. This can help us visualize areas in the country that are poorly connected and have considerable growth potential from efficiency gains in agriculture. Areas from which it takes significantly more time to get to the nearest market and have high (in red) or medium (in orange-red) attainable agricultural potential should be a priority for connecting through secondary roads to the trunk road network.

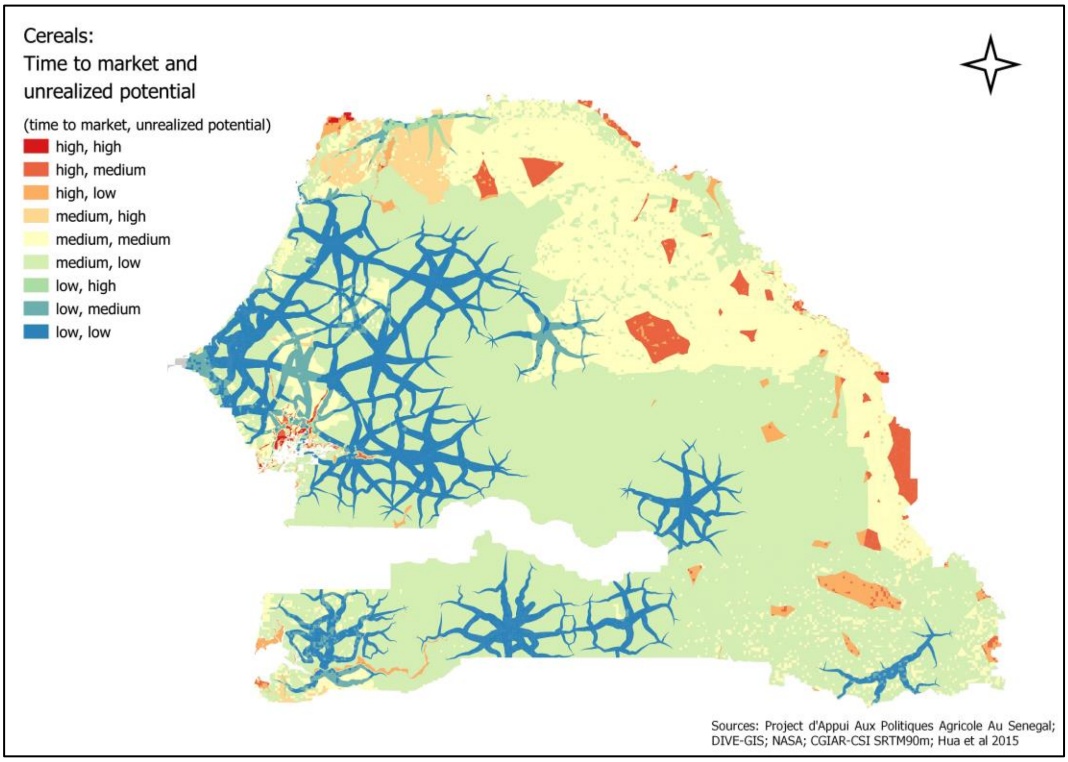

Figure 10. Senegal dry cereals sample: Attainable agricultural potential and time to markets

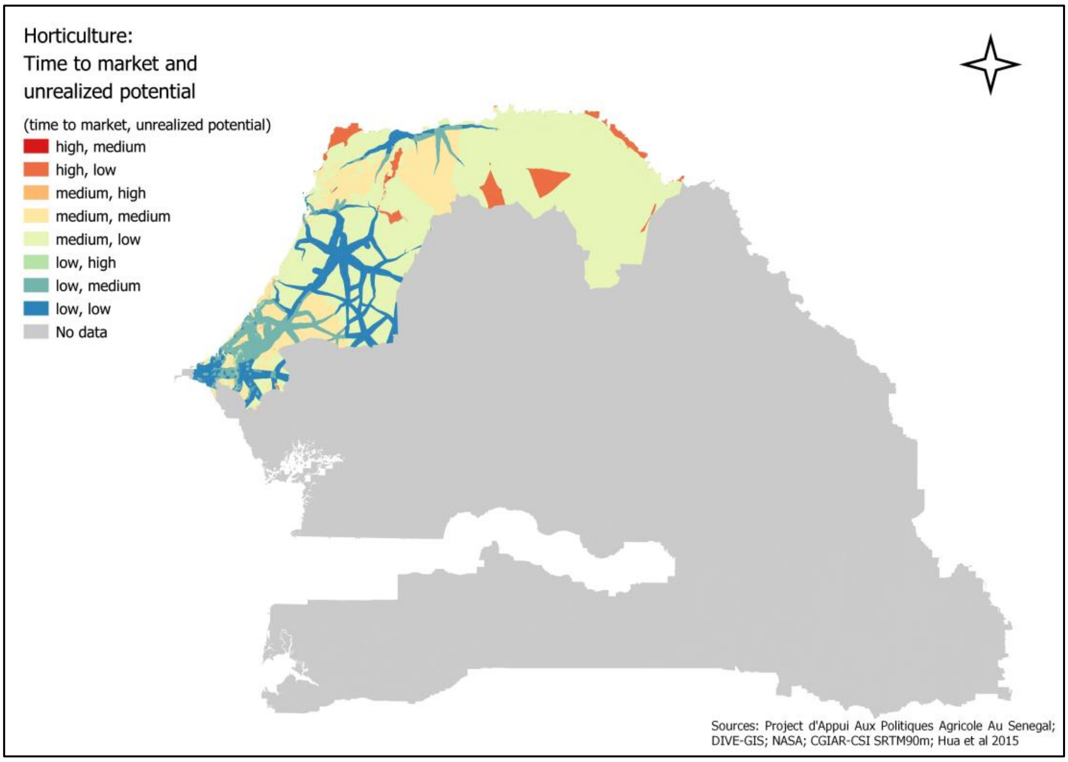

Figure 11. Senegal horticulture sample: Attainable agricultural potential and time to markets

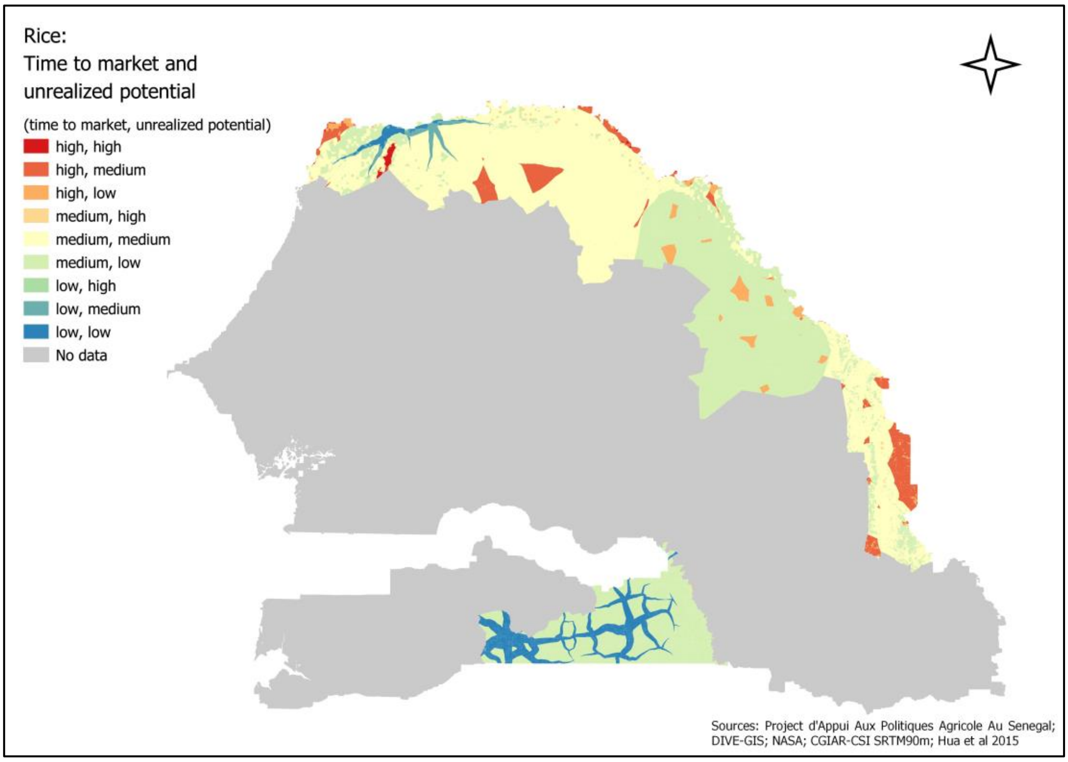

Figure 12. Senegal irrigated rice sample: Attainable agricultural potential and time to markets

4.4.3 Profit gains from small-scale irrigation and rural electrification investments

Figures 13, 14 and 15 show the magnitude of the estimated profit gains from investments in small-scale irrigation in each of the crop samples. This is the expected increase in profits that would result from moving farmers in each sample from their current irrigation adoption status to full adoption, given the constraints to their overall potential imposed by biophysical factors (access to water sources). In the cereal sample (Figure 13), we observe medium to high profit gains for almost the entire country, which reflects the low use of irrigation and high dependence on rainfall for cereal farming in most of the country. An exception are the farmers in the Senegal River Valley who already benefit from irrigation investments originally targeted towards rice production. Results for the horticulture sample (Figure 14) are less relevant given the high rates of irrigation adoption in the sample, and confirm that remaining opportunities for investments in small-scale irrigation are located away from the saturated Senegal River Valley, in this case in the departments of Louga and Rufisque. We find that investments in small-scale irrigation in the Senegal River Valley would only be profitable for the irrigated rice producers sample (Figure 15), together with most of the Anambe Basin.

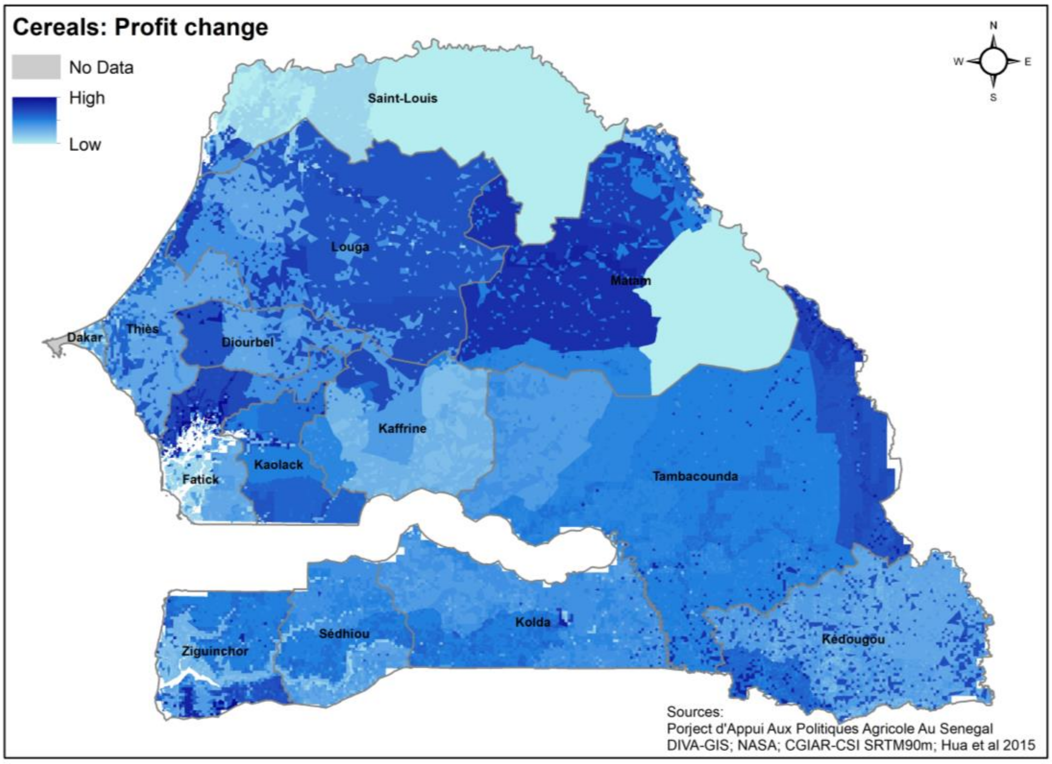

Figure 13. Senegal dry cereals sample: Profit gains from irrigation

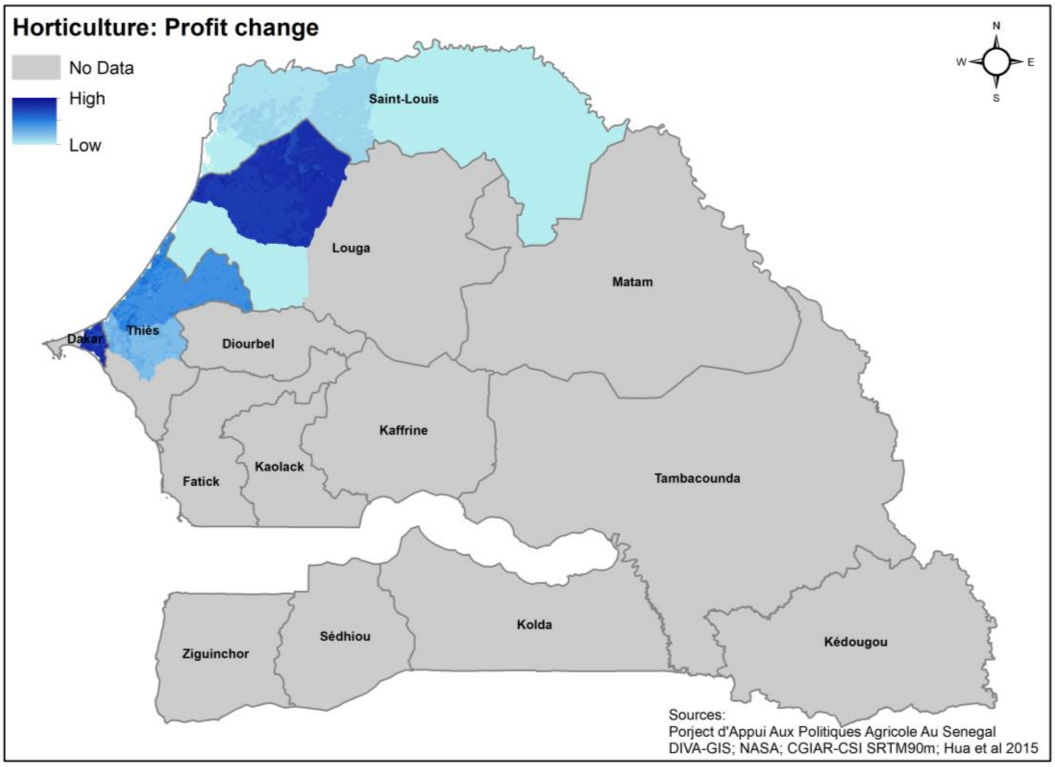

Figure 14. Horticulture sample: Profit gains from irrigation

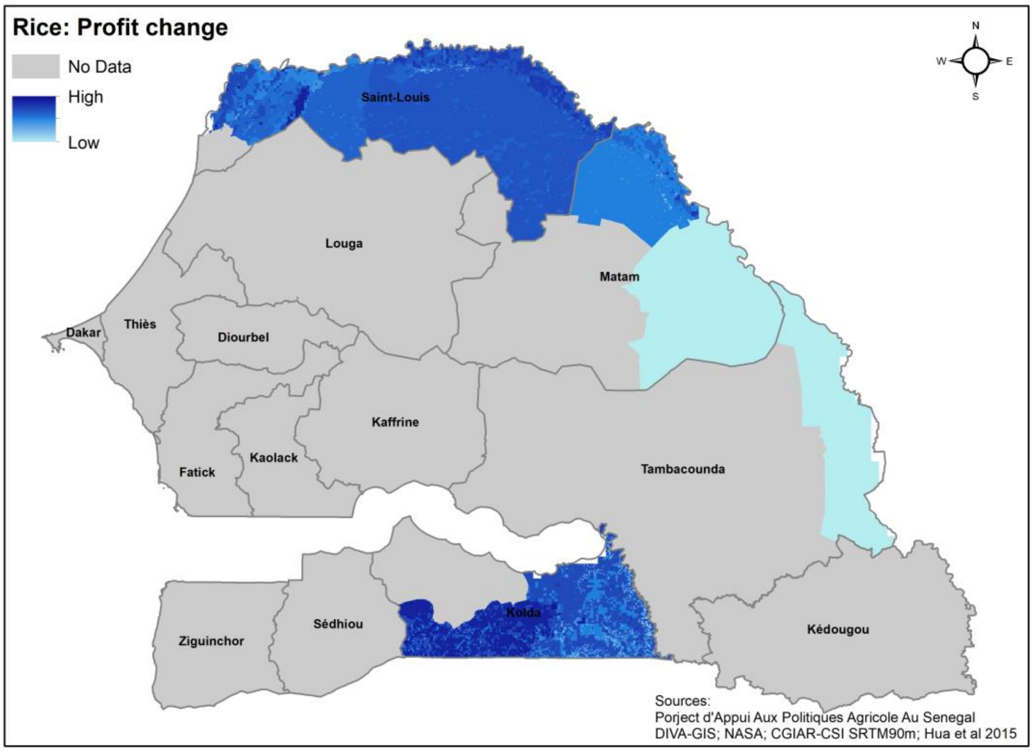

Figure 15. Irrigated rice sample: Profit gains from irrigation

The importance of electricity in the rice value chain in Senegal is illustrated in a study by ENDA (Environment Development Action in the Third World) (GNESD, 2015). According to their study, rice producers in the Senegal River Valley relying on electric water pumps for irrigation had a better performance than those using diesel hydraulic pumps due to cost reasons. While the whole area covered by the rice sample would benefit from electrification, higher profits are expected in the departments of Saint-Louis and Dagana, Bakel, and across all the Anambe Basin, where expansion of the main grid has been slow (Figure 16).

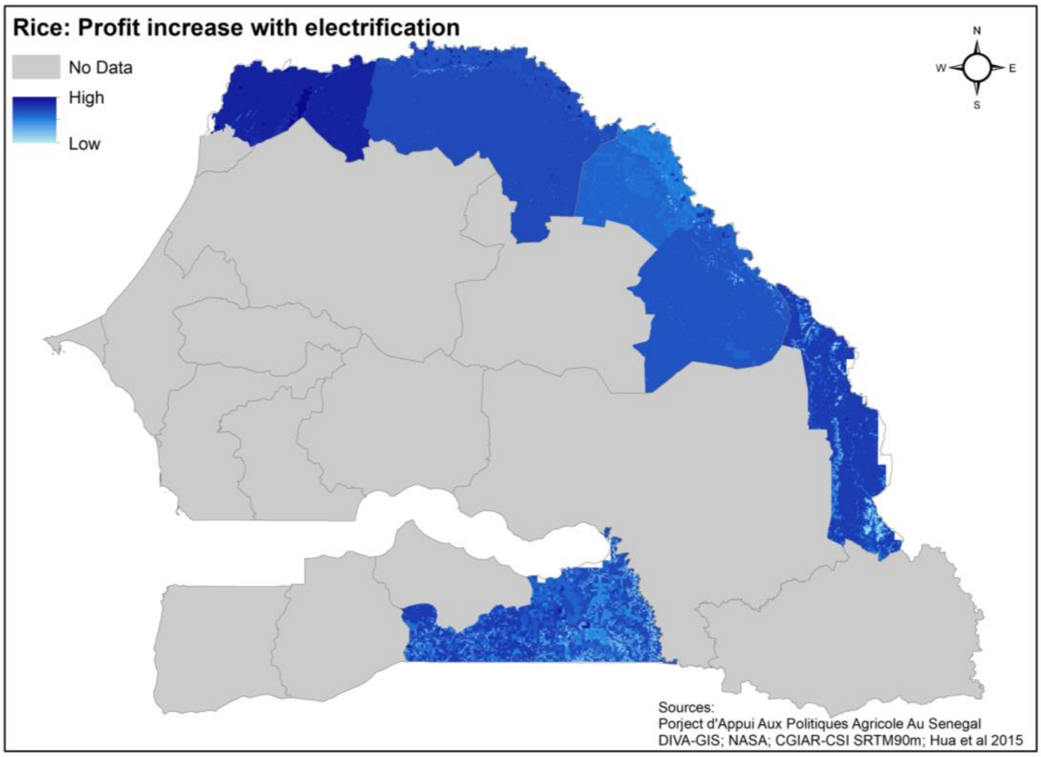

Figure 16. Irrigated rice sample: Profit gains from electrification

4.4.4 Poverty and food security

In this section we discuss very briefly how our analysis is complemented by considerations about the spatial distribution of poverty and nutritional outcomes. Figure 17 shows the regional poverty map for Senegal based on household data from the 2011 *Enquête de Suivi de la Pauvreté au Sénégal* (ESPS-II 2011). In general, the incidence of poverty follows a distinct north-south pattern that closely follows the distribution of agricultural potential in the dry cereals sample shown in Figure 3, with higher poverty rates in the south of the country where the three poorest regions are located: Kolda (76.6 percent), Kédougou (71.3 percent), and Sédhiou (68.3 percent).

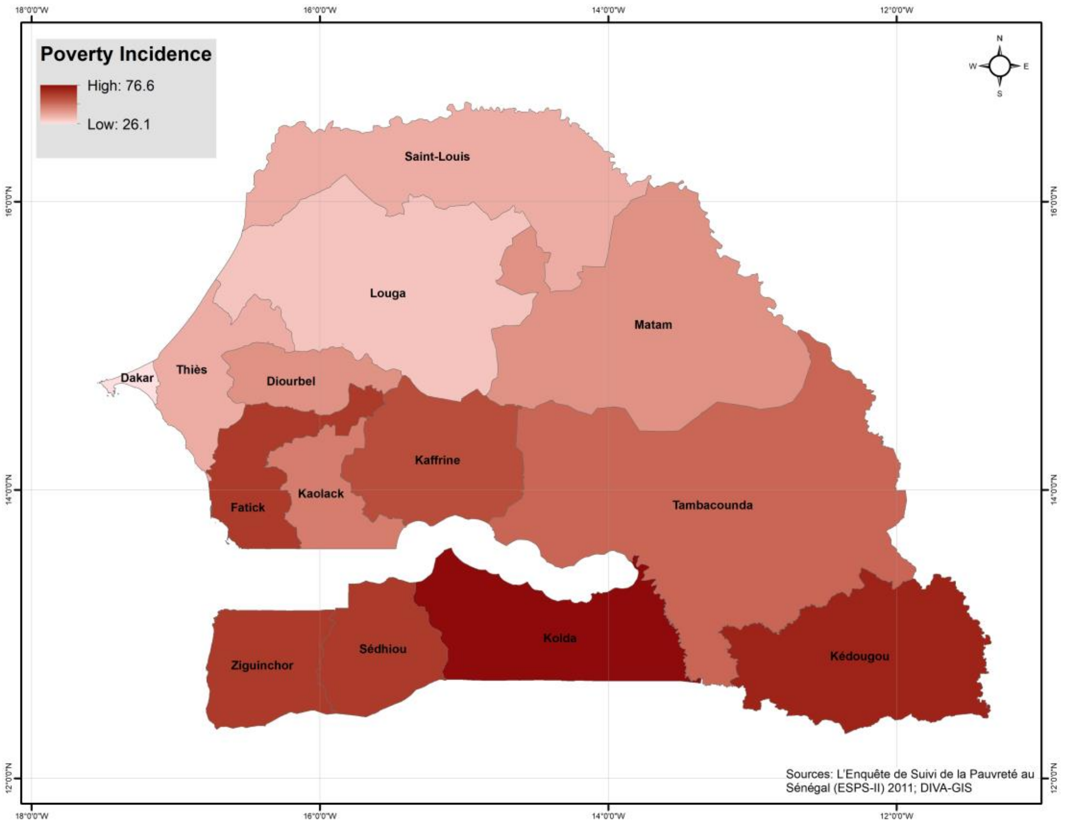

Figure 17. Senegal: Poverty map

To understand the spatial dimension of the food security situation in Senegal, we present maps for stunting (Figure 18) and wasting (Figure 19) from the 2017 *Enquête Démographique et de Santé Continue* (EDS-Continue 2017). Stunting is the impaired growth and development that children experience from poor nutrition, repeated infection, and inadequate psychosocial stimulation. Children are defined as stunted if their height-for-age is more than two standard deviations below the WHO Child Growth Standards median. On a population basis, high levels of stunting are associated with poor socioeconomic conditions and increased risk of frequent and early exposure to adverse conditions such as illness and inappropriate feeding practices. Since stunting prevalence is correlated with socioeconomic poverty and urbanization, it is not surprising that stunting closely tracks poverty, with the more urban and wealthier northern and western regions exhibiting a much lower prevalence of stunting than the central and southern regions. Figure 18 shows that the three poorest regions in the country also suffer from the highest stunting prevalence rates and are in the south: Kolda (31.6 percent), Kédougou (28.8 percent), and Sédhiou (26.6 percent).

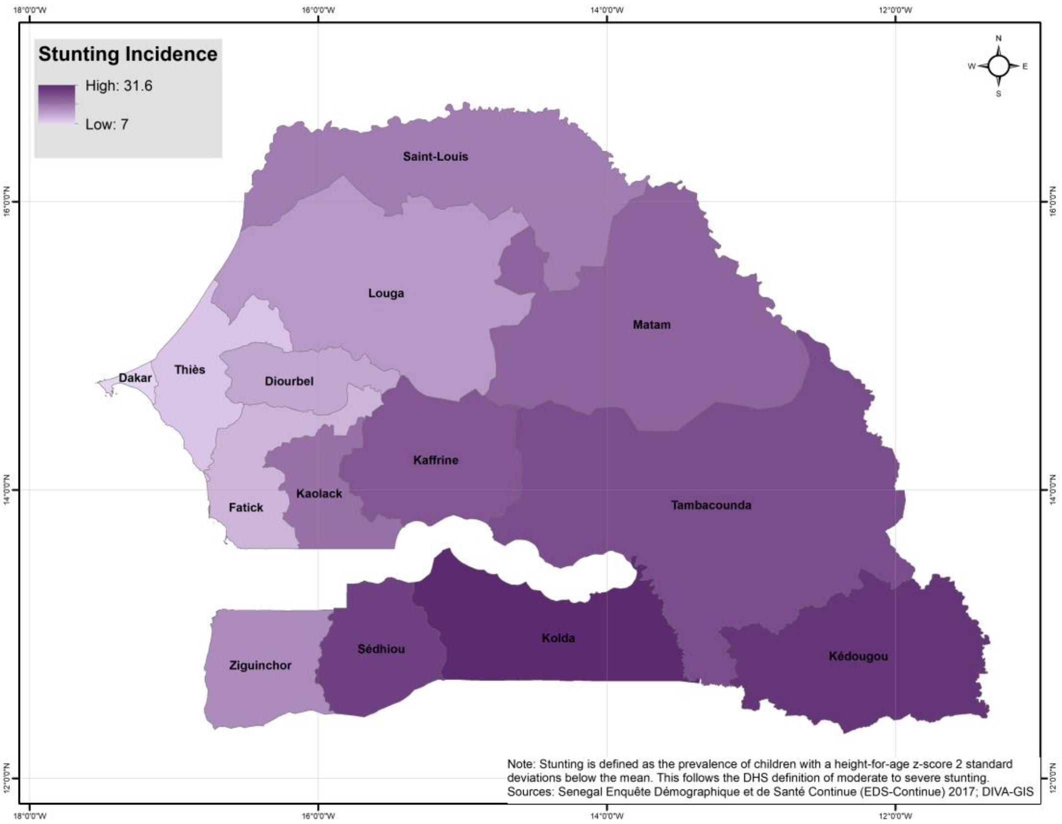

Figure 18. Senegal: Stunting prevalence

While stunting can be considered a longer-term indicator of poor socioeconomic conditions, wasting or low weight-for-height captures exposure to severe negative shocks (food shortages and disease) and can be used as a predictor of child mortality. Children are defined as wasted if their weight-for-height is more than two standard deviations below the WHO Child Growth Standards median. Figure 19 confirms that wasting, being less dependent on poverty and more heavily influenced by external (environmental and geographical) shocks, follows a distinctly different pattern from poverty and stunting, with the regions with the highest wasting prevalence rates being in the northern-central area of the country: Matam (15 percent), Louga (13.8 percent) and Fatick (12.6 percent).

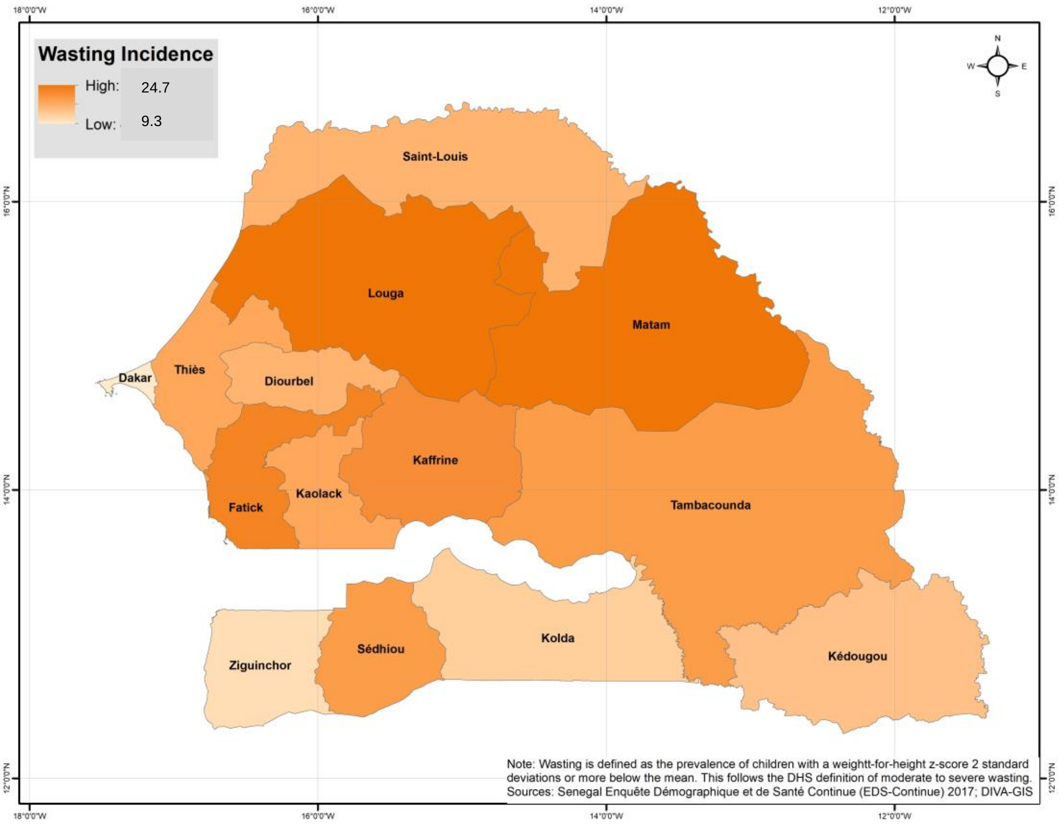

Figure 19. Senegal: Wasting prevalence

The results in the previous sections identified the most promising areas for investments in rural infrastructure by prioritizing areas with the highest expected gains in agricultural revenue from closing productive efficiency gaps. The maps in this section show that while the prioritization strategy that results from such criteria might not be perfectly aligned with policies aimed at reducing poverty and improving nutrition outcomes at the subnational level, some geographic synergies exist and should be considered. Our accessibility maps (Figures 9-12) show, for example, that regions like Kédougou and Matam, suffering from high prevalence rates of stunting and wasting, respectively, should be prioritized for investments in improving and expanding the road infrastructure, but that in terms of closing efficiency gaps in agriculture, Kédougou is much more constrained than Matam, with the latter having better opportunities to enjoy significant gains from its attainable agricultural potential.

5. Conclusions

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 roads, agriculture, small-scale irrigation and rural electrification are in Senegal. 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 the stochastic frontier analysis (SFA) to (i) identify areas of high agricultural potential with low accessibility to prioritize investments in road infrastructure according to a spatial model that estimates the minimum time taken to travel from any point in a country to the nearest market, and (ii) estimate average household gains in agricultural efficiency by comparing smallholders' performance under current conditions and under separate scenarios of improved access to small-scale irrigation and rural electrification. Our analytical results and typology maps highlight the spatial heterogeneity in opportunities and priorities for road infrastructure, small-scale irrigation and electrification investments.

In Senegal, the largest concentration of high agricultural potential areas for cereals is found in the region of Saint-Louis in the north, specifically in the departments of Dagana and Podor. Good access to surface water and proximity to agricultural markets and large urban areas (Saint-Louis) help explain this finding, despite generally low annual rainfall levels and land erosion and degradation issues. Other areas with high agricultural potential are Rufisque in the Dakar region, with immediate access to the capital and a shallow aquifer in the Niayes area, and Ziguinchor in the Casamance region, with the highest annual rainfall level in the country and better access to markets than neighboring areas with similar agroecological conditions. Areas in Dagana, Podor, Kanel, Ranerou-Ferlo, Matam, Kanel, Fatick, Bambey, Rufisque, Ziguinchor, and Bakel with medium to high agricultural potential and medium to low efficiency are key targets for investments in small-scale irrigation.

In the case of horticulture, the areas with higher potential are in Rufisque, Thies, and Tivaouane, and benefit from their proximity to the largest cities in the country, Dakar and Thies. To a lesser extent, Dagana also shows considerable agricultural potential due to its proximity to Saint-Louis and the presence of processing industries that demand several crops such as tomatoes and rice. There are no evident areas to target with investments in small-scale irrigation investments in this sample given the high percentage of horticultural farmers already using irrigation.

For the rice producers' sample, the divide in the distribution of potential is very clear with medium to high potential in the Senegal River Valley (north), and medium to low potential in the Anambe Basin (south), which is explained by better market accessibility in the Senegal River Valley and a longer history of government and donor support in the region. In combination with the agricultural efficiency estimates, these results show that farms in Podor (Saint-Louis) are among the best targets for investments in small-scale irrigation given their high potential and low efficiency levels.

In terms of the expected profit gains from investments in small-scale irrigation, we observe medium to high gains for almost the entire country, which reflects the low use of irrigation and high dependence on rainfall for cereal farming in most of the country. An exception are the farmers in the Senegal River Valley, who already benefit from irrigation investments originally targeted towards rice production. Results for the horticulture sample are less relevant given the high rates of irrigation adoption among these producers, and confirm that remaining opportunities for investments in small-scale irrigation are located away from the saturated Senegal River Valley, in this case in the departments of Louga and Rufisque. Only for the irrigated rice producers sample we observe that investments in small-scale irrigation would be profitable in the Senegal River Valley, together with most of the Anambe Basin.

In the case of profit gains from investments in rural electrification applied to the rice producers' sample, we observe that while the whole area covered by the sample would benefit from electrification, higher profits are expected in the departments of Saint-Louis and Dagana, Bakel, and across all the Anambe Basin, where expansion of the main grid has been slow.

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Annex: Methodology

GIS market accessibility model

The market accessibility model applies spatial analysis using GIS variables to simulate the shortest amount of time it takes to travel between any two different points in the country. The model was developed on a raster format, where the entire area of analysis was converted into a grid of cells measuring 25 by 25 meters each. The first step to estimate the accessibility model is to assign each of these cells a *friction* value, which represents the time it takes to travel through the cell, based on the availability and quality of roads, the slope, and the presence of natural barriers.

Typically, roads in a network can be categorized as first order roads, second order roads, dirt road tracks, and walking trails. When first and second order roads are present in a cell, its crossing time can be calculated using the following equation:

$$\text{Cell crossing time (seconds)} = 92.6 \times \left(\frac{1}{\text{Speed (Km/hr)} \times \left(\frac{1000}{3600}\right)} \right) \quad (1)$$

Assuming specific travel speeds for first and second order roads (plus river navigation) results in the following cell crossing times:

Table A1. Average speed and cell crossing time by type of road (first and second order)

Type of road	Average travel speed (km/h)	Cell crossing time (secs)
First order road	60	5
Second order road	30	11
River navigation	10	33

Source: Own elaboration

For roads classified as dirt road tracks and walking trails, the slope variable is used to calculate walking speeds. The walking velocity is calculated using the following equation from Tobler (1993):

$$\text{Walking velocity on footpath} = [6 \times \exp(-3.5 \times \text{abs}(S + 0.05))] \quad (2)$$

where S represents the slope. Finally, the walking velocity by type of road (dirt road, walking trail, and no road) is calculated as shown in Table.

Table A2. Average speed by type of road (dirt road tracks, walking trails, and no roads)

Type of road	Average speed (km/h)
Dirt road tracks	Walking velocity on footpath × 1.25
Walking trails	Walking velocity on footpath
No roads	Walking velocity on footpath × 0.6

Source: Own elaboration

Finally, the model considers the presence of natural barriers –in this case non-navigable rivers, which prevent people from traveling in a straight line unless there is a bridge. Cells corresponding to areas with a river and no bridge are assigned a travel time 10 times their value.

With the assumptions and equations presented above we build the friction model and allocate a travel time value to each cell. Then we run cost-weighted distance algorithms over the raster surface to choose the optimal route between any two points in the area of analysis that minimizes the accumulated travel time. 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.

GIS water access and slope measures for the small-scale irrigation analysis

The biophysical suitability for small-scale irrigation is captured by two variables: the first denoting the accessibility to surface and ground water, and a second capturing the suitability of the slope for irrigation. These variables are inputs to the work done by Xie, et al. (2018) to predict irrigation expansion in Africa's drylands by 2050. The first step was to estimate the pixel-level suitability for small-scale irrigation, where small scale irrigation is defined as the use of treadle pumps, motor pumps, small reservoirs, and ponds managed by individuals or local communities. These suitability scores are then used, along with other inputs, to simulate the expansion of irrigation for the 2050-time horizons. Slope and water access are two of the criteria considered in creating the small-scale irrigation suitability index; the other criteria being proximity to existing irrigation and market access. We've included the slope and water access components of the index rather than the full small-scale suitability index because of our need to characterize the biophysical components of irrigation use rather than the market constraints, which are already included in the frontier estimation through market access and prices.

Water accessibility is measured on a scale from 0 to 100 where a score of 100 is given if the area is within the spatial extent of surface water bodies indicated by the Global Lakes and Wetlands Database level-3 database. This is a database developed by WWF and the Center for Environmental Systems Research at the University of Kassel that contains the maximum extent of permanent surface water bodies, including lakes, rivers, reservoirs, and wetlands. If a location is outside of this area, then the suitability is determined by the accessibility of ground water as categorized by the British Geological Survey's digital ground water depth map of Africa. A score of 70 is given if the groundwater is very shallow, 40 if it is shallow, 20 if it is medium shallow, and 0 if it is medium. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the water access index map for Burkina Faso. Most of the land area of the country is considered to have moderate suitability for irrigation in terms of water access with approximately 62 percent of the area given an index value of 40. Approximately 24 percent of the area is considered suitable or highly suitable with a score of 70 or higher. For Senegal (Figure), most of the land area is considered marginal or highly marginal with approximately 38 percent of the area given an index value of 20 and 25 percent given an index value of 0. Only 7 percent of the country is considered highly suitable.

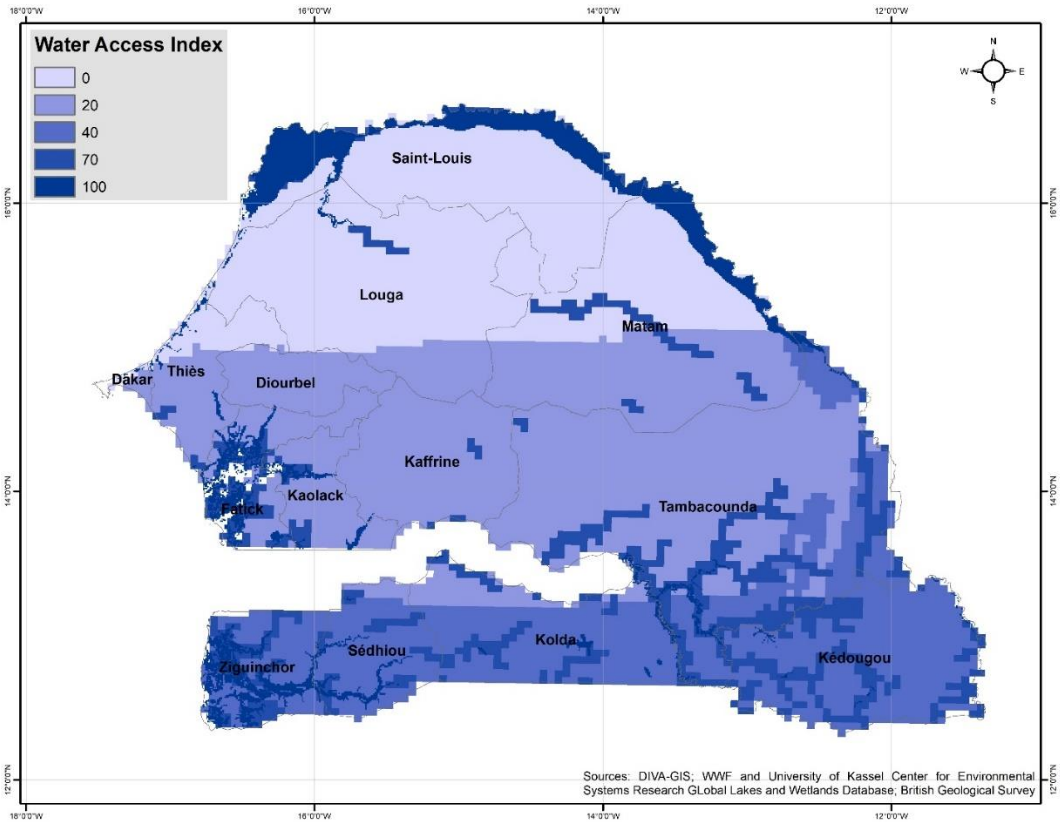


Figure A1. Water access index

Similarly, slope is measured on a scale between 0 and 100 where 100 denotes most suitable and 0 indicates unsuitable. We use the WWF's HydroSHEDS Digital Elevation Model (DEM). An area is given a score of 100 if the grade is less than 2 degrees, 70 if the grade is between 2 and 4 degrees, 40 if it is between 4 and 7 degrees, 20 for areas between 7 and 10 degrees, and a value of 0 is assigned if the grade is greater than 10 degrees. **Fehler! Verweisquelle konnte nicht gefunden werden.** shows the slope index map for Burkina Faso. 84 percent of the land area of the country has a slope of less than 2 degrees and is given an index value of 100 while only 1 percent has a slope of 7 degrees or higher. 90 percent of the land area of Senegal (Figure 20) has a slope of less than 2 degrees and is given an index value of 100 while only 0.7 has a slope of 7 degrees or higher.

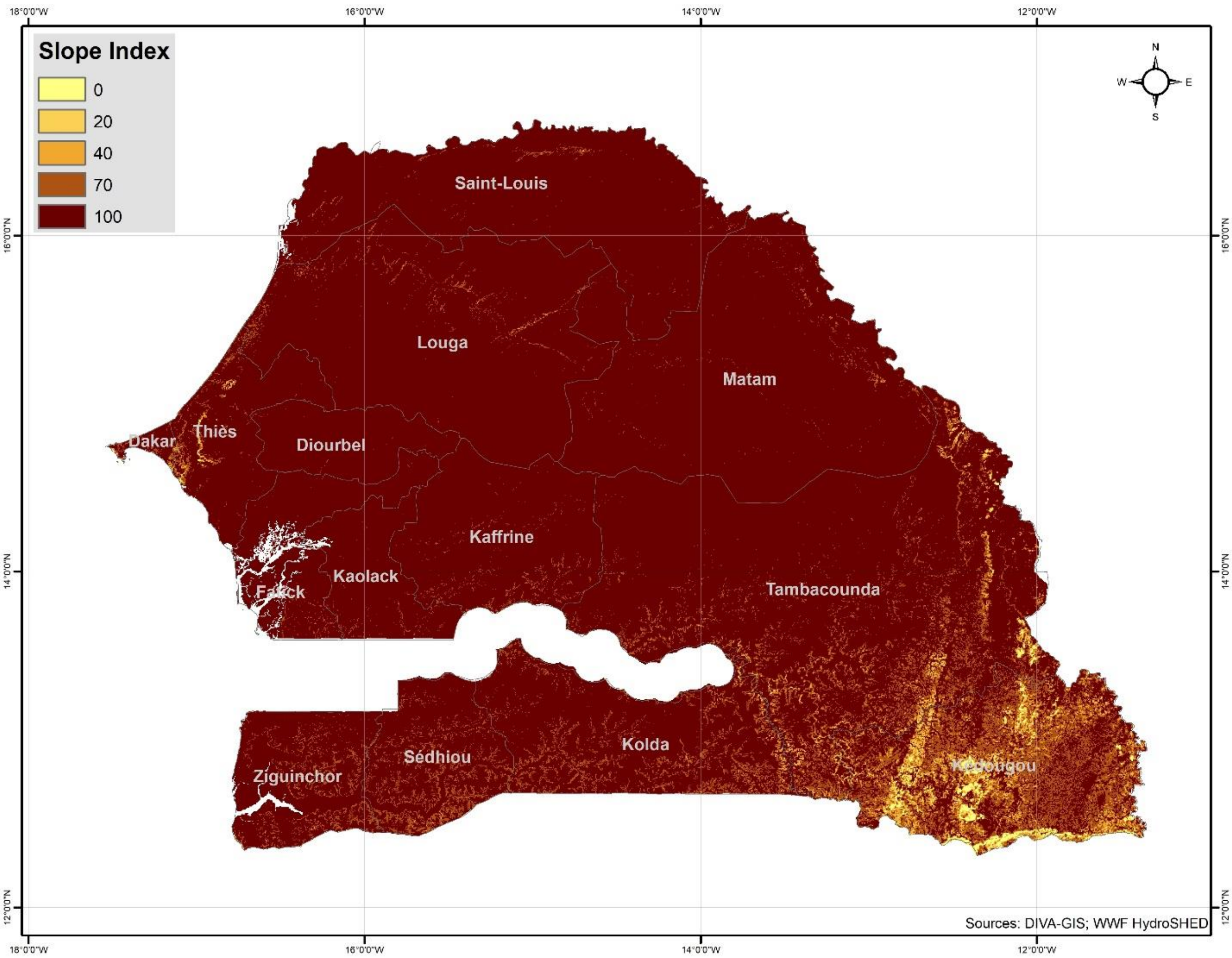


Figure 20. Slope index

Heckman selection model for the rural electrification analysis

To assess the impact of increasing access to electricity on smallholders, we first need to estimate what would the electricity consumption be for those households that do not have access to the service yet. Therefore, we need to estimate the following underlying relationship:

$$ec_i = h_i\gamma + \mu_{1i} \qquad (3)$$

where ec_i is the electricity consumed by household *i* during a given period, h_i is a vector of household characteristics, and μ_{1i} is an error term distributed $N(0, \sigma)$. However, electricity consumption is only observed if the household is connected to a service provider if:

$$q_i\theta + \mu_{2i} > 0 \qquad (4)$$

where q_i is a vector that includes factors that determine whether household *i* is connected to a service provider, μ_{2i} is an error term distributed $N(0,1)$, and $\mathrm{corr}(\mu_1, \mu_2) = \rho$.

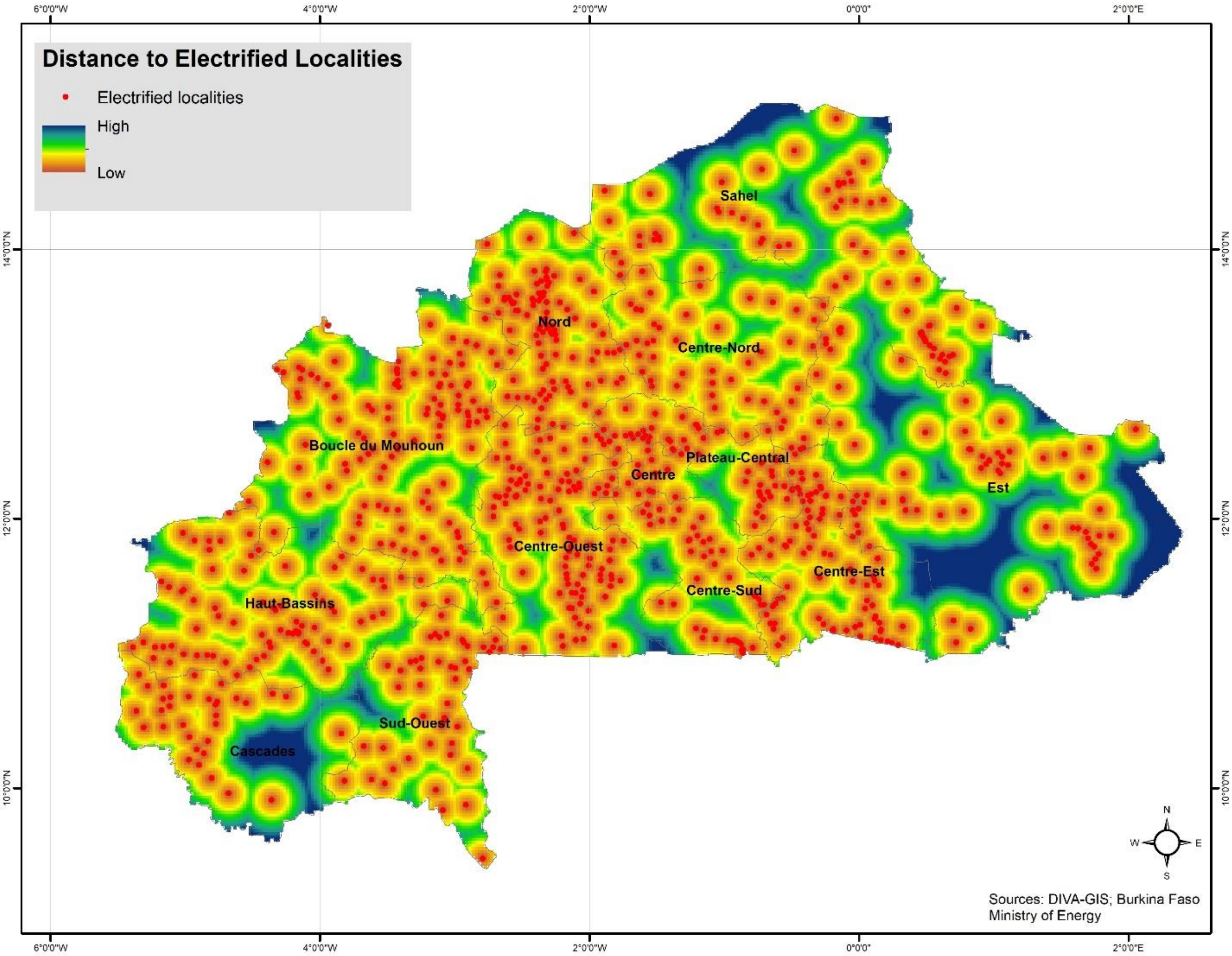


Figure 21. Burkina Faso: Distance to electrified localities

Heckman's approach (Heckman, 1976) provides consistent, asymptotically efficient estimates for all the parameters in this model if variables that strongly affect access to electricity but not consumption can be found. Given the available data, we use the average distance to the nearest electrified locality (Figure 21) for Burkina Faso, and the household's distance to the closest medium voltage line (Figure 22) and a nighttime luminosity index (Figure 23) for Senegal, as measures that explain access to electricity, but not directly determine consumption.

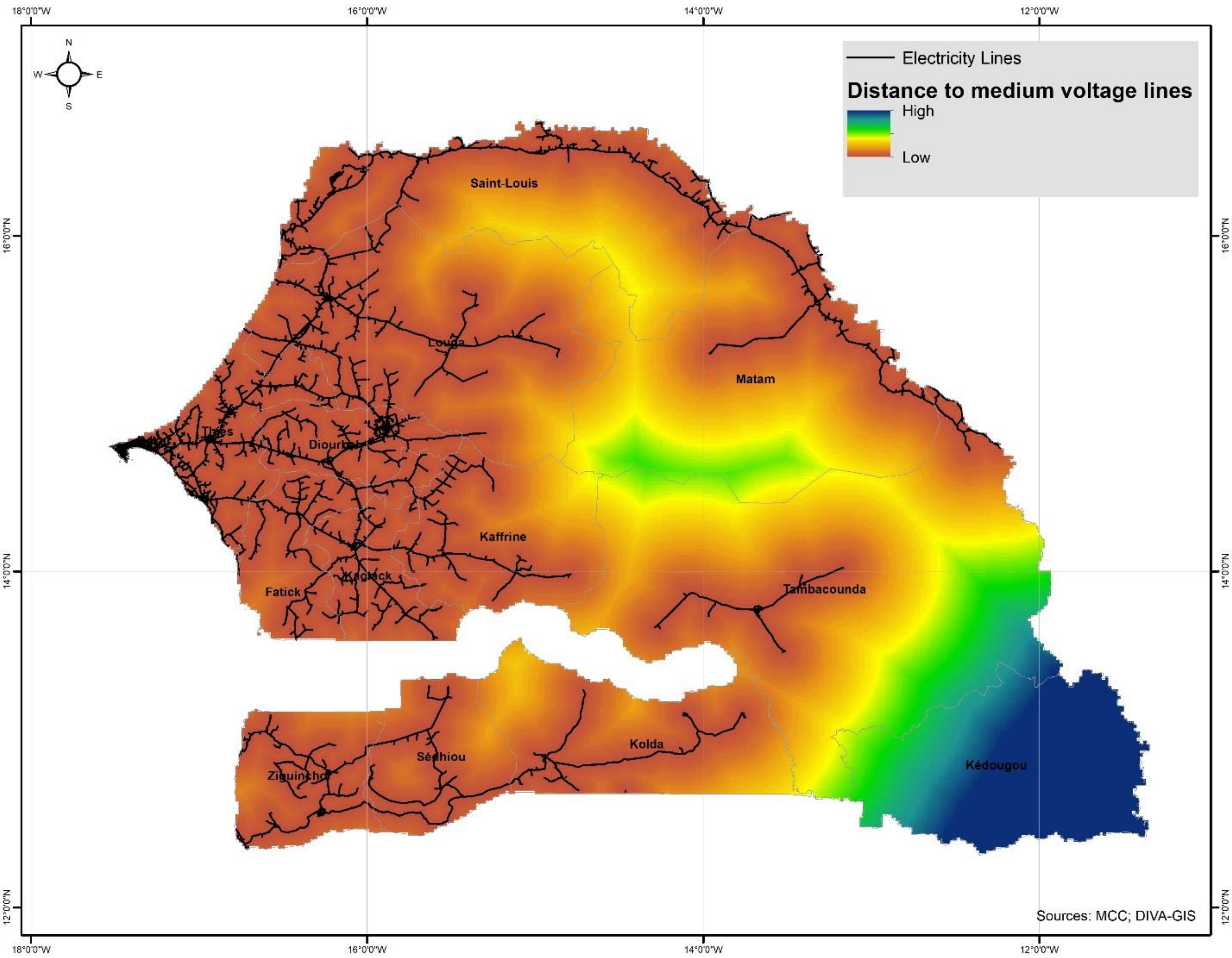


Figure 22. Senegal: Distance to medium voltage lines

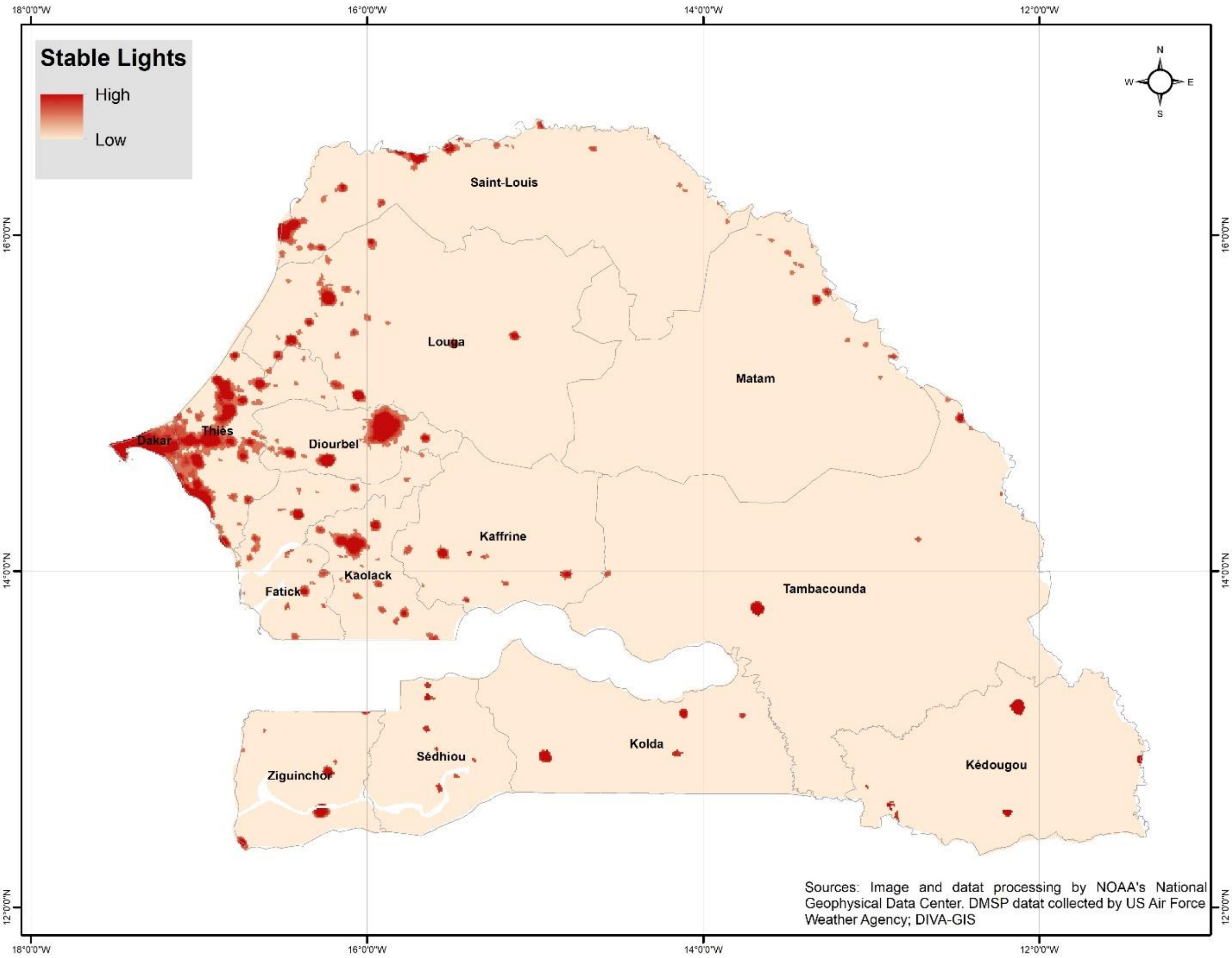
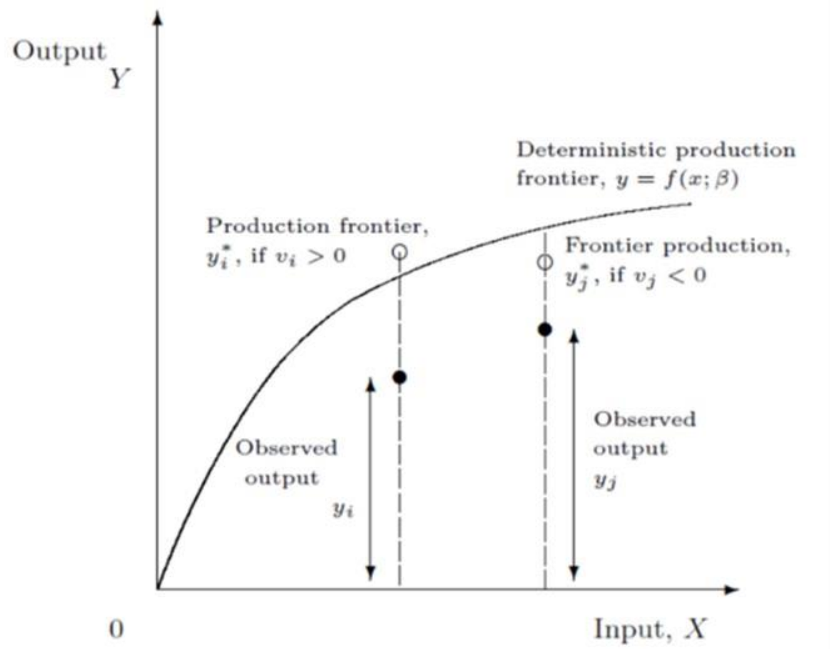


Figure 23. Senegal: Nighttime lights index (2011)

Stochastic frontier analysis

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 & 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 data to econometrically estimate the parameters of that function.[11] 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 which is an important feature when analyzing agricultural activities constantly exposed and extremely sensitive to random shocks. 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.[12]

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 24.



Source: Own elaboration

Figure 24. 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:

$$y_i = f(x_i; \beta)\exp(v_i - u_i) \quad (5)$$

[11] See Park & Simar (1994), Kumbhakar & Tsionas (2008), and Martins-Filho & Yao (2015) for semi-parametric approaches to SFA that relax some of its parametric functional form requirements.
[12] The main cost of using SFA is that it requires more detailed data to model the efficiency term and, as in any parametric approach, it relies on making the correct choice of functional form.

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 or her current production.

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

$$TE_i = \frac{y_i}{y_i^*} = \frac{f(x_i;\beta)\exp(v_i - u_i)}{f(x_i;\beta)\exp(v_i)} = \exp(-u_i) \quad (6)$$

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 to 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:

$$\sigma_{u_i}^2 = \exp(z_i\delta) \quad (7)$$

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

To estimate the model expressed by equations (3) - (5) 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):

$$\pi_i = f(p_i, w_i;\beta)\exp(v_i - u_i) \quad (8)$$

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

Farm-specific characteristics and conditions in which its productive activities take place affecting the smallholder's technical efficiency and determined by decisions made at the local level by the household or community in the short term are included in the vector z_i, referred to in (7). Typically, the effect of factors included in z_i cannot be captured by a price or set of prices due to market failures often found in the context of agricultural activities in developing countries. For this study, we incorporate the following variables of z_i in the econometric analysis:

- *Farm size*: Number of hectares of land managed by the farmer. In contexts where smallholders have little access to land and credit markets (or these are not properly developed) the effect of land and land availability cannot be fully captured with the price of land in the deterministic portion of the stochastic frontier. Therefore, the amount of land the farmer currently manages restricts his scale and is a source of inefficiency that needs to be included in the error term.
- *Farm assets*: Value of farm assets to proxy for other capital inputs.

- *Household size*: Number of household members. The small scale and low revenue stream of many of these farms does not always allow them to hire labor to adjust their scale to seasonal changes and market trends, which makes them rely more heavily on the household's labor supply.
- *Characteristics of the household head*: Depending on each particular context, the gender and education of the household head can proxy for the farmer's access to information and opportunities that affect the performance of the productive unit.

In addition to these factors, in an agricultural context it is necessary to consider other conditions that affect the farm's potential that cannot be easily modified in the short or medium term, such as the climate or 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 (8) becomes: