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Targeting Small-Scale Irrigation Investments using Agent-Based Modeling: Case Studies in Mali and Niger

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Abstract

Small-scale irrigation has been identified as a potential adaptation strategy for climate change and boosting food security and livelihoods in dry regions. This study presents the analysis of the potential adoption of small-scale irrigation in two West African countries (Mali and Niger) by using a spatially explicit analytical framework. It underscores the need for strategically investing in the management of ground and surface water resources for the development of small-scale irrigation systems in the two countries. The study implemented an agent-based modeling technique to simulate small-scale irrigation decisions at the district and national level. The results revealed that, while small-scale irrigation can increase crop productivity in both countries, its adoption may be constrained by water scarcity and tensions in water allocation. Strategic water resource development plans should be established to ensure efficient and sustainable irrigation schemes, especially for areas with high potential profitability.

Keywords: small-scale irrigation, agent-based modeling, West Africa, Mali, Niger

JEL codes: C63, Q15, Q16

1. Introduction

Agricultural growth is an important key to reduce rural hunger and extreme poverty in Africa (Rosegrant et al., 2005). Irrigated agriculture, specifically, can help African countries to improve and to sustain agricultural productivity while reducing food insecurity and importation dependency. Irrigated agriculture currently accounts for only 20 percent of cropland in Sub-Saharan Africa, yet it contributes 40 percent of total production in the region (FAO and OECD, 2016). Irrigation can also promote regional development by improving nutritional outcomes and combating poverty in rural areas (FAO, 2017a).

In West Africa, there is an important knowledge gap with regard to the drivers of irrigation adoption in general. Several studies (e.g., Devereux, 2016; van Ittersum et al., 2016; Garrity et al., 2010; Webber and Hill, 2014) have shown that the strategic deployment of technologies, where institutions and policies in agriculture and related sectors work together for a shared goal, is necessary for achieving food security. In most analyses, however, the expansion rate of irrigated agriculture was introduced as an exogenous variable with no analytical basis. Few studies attempted to estimate the availability and sustainable use of surface water and groundwater resources in irrigation (MacDonald et al., 2011; Xie et al., 2014; You et al., 2011).

In recent years, a renewed interest has been given to the promotion of small-scale irrigation for the production of cereal and vegetable crops. Small-scale irrigation refers to small irrigation schemes (facilitated by public and private sectors) developed to harvest water resources to augment crop production under private ownership of farmers. Irrigation water can be fed by groundwater or surface water (Xie et al. 2018). Small-scale irrigation enables farmers who would otherwise have to depend on irregular and variable rainfall to increase crop intensities through multiple cropping by supplementary watering during dry season or drought as well as enabling crop and forage growth in dry areas for crop expansion (Xie et al., 2014; Xie et al., 2018). Unlike large-scale irrigations that rely on large dams and thus require significant financial and management resources, small-scale irrigation systems are less expensive and more easily adaptable to different types of cropping and farming systems managed by farming communities (You et al., 2014; Xie et al., 2017). Small-scale irrigation has a larger effect on agricultural production and agricultural income than large-scale irrigation and thus can have more direct effects on food security and poverty reduction (Rosegrand et al., 2005). Hence, the adoption of small-scale irrigation is increasingly advocated for its potential in promoting efficient land resource management, environmental resilience, and economic sustainability of food and agriculture systems (FAO, 2018; Olayide, Tetteh, and Popoola, 2016; Xie et al., 2014; Tafesse, 2003).

However, small-scale irrigation cannot be applied everywhere due to the specificity in the types of irrigation, land suitability, and potential profits considering the investment cost (Xie et al., 2014; Xie et al., 2017). The assessment of the probability of adoption and profitability of small-scale irrigation is compelling for low-income countries with heterogeneous agro-ecology, the majority of the population being dependent on agriculture, and an agriculture-based economy (Kegna and Dembele, 2018; Aw and Diemer, 2005; Thom and Wells, 1987). Proper targeting for small-scale irrigation investment is required in these countries through evidenced-based policy making on the suitability of the investment by ensuring the reduction on risks, profitable returns to the investment, and poverty reduction (Eneyew et al., 2014). Many factors, including market access and the suitability of irrigation, are important for absorbing the net surplus from an irrigation farming system (Dillon, 2011). Venot and Cecchi (2011) support that a better perception of opportunities and constraints is necessary for agricultural technologies in general, but especially for small-scale irrigation, which remains understudied compared to large hydraulic installations. The main factors influential to the suitability of small-scale irrigation are usually related to the typology of irrigation water, land characteristics, and market prices. Surface water and groundwater resources are highly variable across Sub-Saharan Africa in general, and the latest climate scenarios suggest that variability and uncertainty will continue to increase (Gan et al., 2016; Vörösmarty et al., 2000). Land characteristics and their irrigation potentials are also impacted by climatic hazards, urbanization, and soil-degrading human actions. Ecosystems and their quantitative groundwater requirements depend on the hydrogeological configuration of the region, the size of the aquifers, and the climate (Tomlinson, 2011). However, information on the functioning of these ecosystems is often not spatially-explicit (Xie et al., 2018).

Small-scale irrigation can potentially provide an immediate entry point for investment in the agriculture sector in West Africa. However, the returns to investments in irrigation (whether large-scale or small-scale) in the region are still unsubstantiated as most irrigation projects have not carried out an impact assessment for suitability and sustainability in a spatially-explicit way. To this end, we define the main objective of this study to evaluate the small-scale irrigation potential and its profitability in Mali and Niger. For each country, we assessed the following research questions:

1. What is the level of small-scale irrigation suitability, and where?
2. What are the most important criteria influencing small-scale irrigation suitability?
3. What are the policy options for supporting the adoption and profitability of small-scale irrigation?

We use an integrated biophysical and economic modeling approach to quantitatively assess the irrigation development potential and estimate the potential of small-scale irrigation expansion. This study builds on the analytical framework used in previous studies at a continental scale in Africa (Xie et al., 2014; You et al., 2014) and at the country level in Nigeria (Xie, You, and Takeshima, 2017) and Kenya (You et al., 2014). By establishing the suitability of different factors for irrigation from these different approaches, this study highlights the areas where small-scale irrigation adoption is likely to happen. We anticipate that the findings of this study will support the efforts being made to develop effective small-scale irrigation investments in the region.

2. Description of Study Sites

2.1. Mali

Mali is a low-income country. Most of its population lives in rural areas, and the economy has remained largely based on agriculture (Kegna and Dembele, 2018; Aw and Diemer, 2005; Thom and Wells, 1987). Agriculture currently accounts for more than 35 percent of the gross domestic product (GDP) and 80 percent of livelihoods. The GDP of the country increased from 8.1 percent in 2007 to 13.1 percent in 2015. Similarly, GDP per capita (current US$) increased from 592.0 in 2007 to 744.3 in 2015. Agricultural value added (annual growth in percent, average 2007-2015) was 11.5 percent. The total land area equipped for irrigation (ha) as of 2013 was 380,000 ha (FAO, 2017b).

Agricultural production is mainly rainfed. Irrigated agriculture is one of the main lines of action that the government of Mali supports to increase food security, promote agricultural investment, and secure income of smallholder farmers (FAO, 2018). The National Strategy for the Development of Irrigation (NSDI) of Mali was developed in 1999 to enable partnerships between the government, beneficiaries, and the private sector to accelerate the pace of hydro-agricultural developments (Republic of Mali, Ministry of Agriculture, 2009). Progress in the development of irrigation agriculture in Mali can be attributed to the historical development and reform of the Office du Niger irrigation scheme. The immediate impact of the reform increased crop production, yields, crop diversification, cropping intensity, farm incomes, food security, and poverty reduction (Aw and Diemer, 2005). Given the high population growth, there is a need to expand irrigated land and growing periods to increase food production in Mali. Similarly, the adoption of irrigation in Mali has been found to have multiple impacts on households' diversification of investment portfolios, food security, and social capital development. Dillon (2011) reported that households with irrigation saved between 4.5 and 6.4 more tropical livestock units and are 20 percent more likely to engage in informal food sharing with non-irrigators.

To this end, the government of Mali has developed a Small-Scale Irrigation Promotion Programme 2012-2021, which aims to fund projects falling into the following categories: surface water systems from major river systems; inland valley basements/lowlands; development of ponds; micro-dams, water harvesting systems, and water retention works in wadis and oasis; irrigated vegetable gardens; pedal pumps, aeolian pumps, electric pumps; and motor pumps (Kegna and Dembele, 2018). Small-scale irrigation in Mali has a larger potential effect on agricultural production and agricultural income compared to large-scale irrigation. However, it is not yet clear whether small-scale irrigation can bring about broad agricultural transformation in low-income economies (You et al., 2011; Tesfaye et al., 2008; Kimmage, 1991).

Mali has diverse agro-ecological conditions across three regions (northern, southern, and delta). The southern part of Mali represents 18 percent of the country's land area and has the longest growing seasons of 160 days. The northern part represents 51 percent of the land area with a growing season of less than 15 days while the central zone, which includes the inland delta of the River Niger, makes up 26 percent of the land in Mali and has a highly variable growing season (15 to 100 days) (Schrecongost, 2005). Small-scale irrigation technologies are more common in the northern zones of Mali (including Bandiagara, Niono, Ségou, Gao, Tombouctou, and Mopti regions), which typically receives 200-600 mm of rainfall per annum, located along the Niger river (Figure 1). Irrigation by gravity is also used on small irrigated areas for cereals (rice, wheat, maize) and vegetable production. Small-scale irrigation is mainly used by resource-poor smallholder farmers. Millet, sorghum, rice, and maize are the basic food crops cultivated under small-scale irrigation. The *Office du Niger* lies in the inland delta; the small, irrigated village perimeters (PPIVs) are located primarily along the Niger River in Mopti, Gao, and Tombouctou. Lowlands are included in small-scale schemes located in southern (Sikasso) and western Mali (Kayes) (Figure 1).

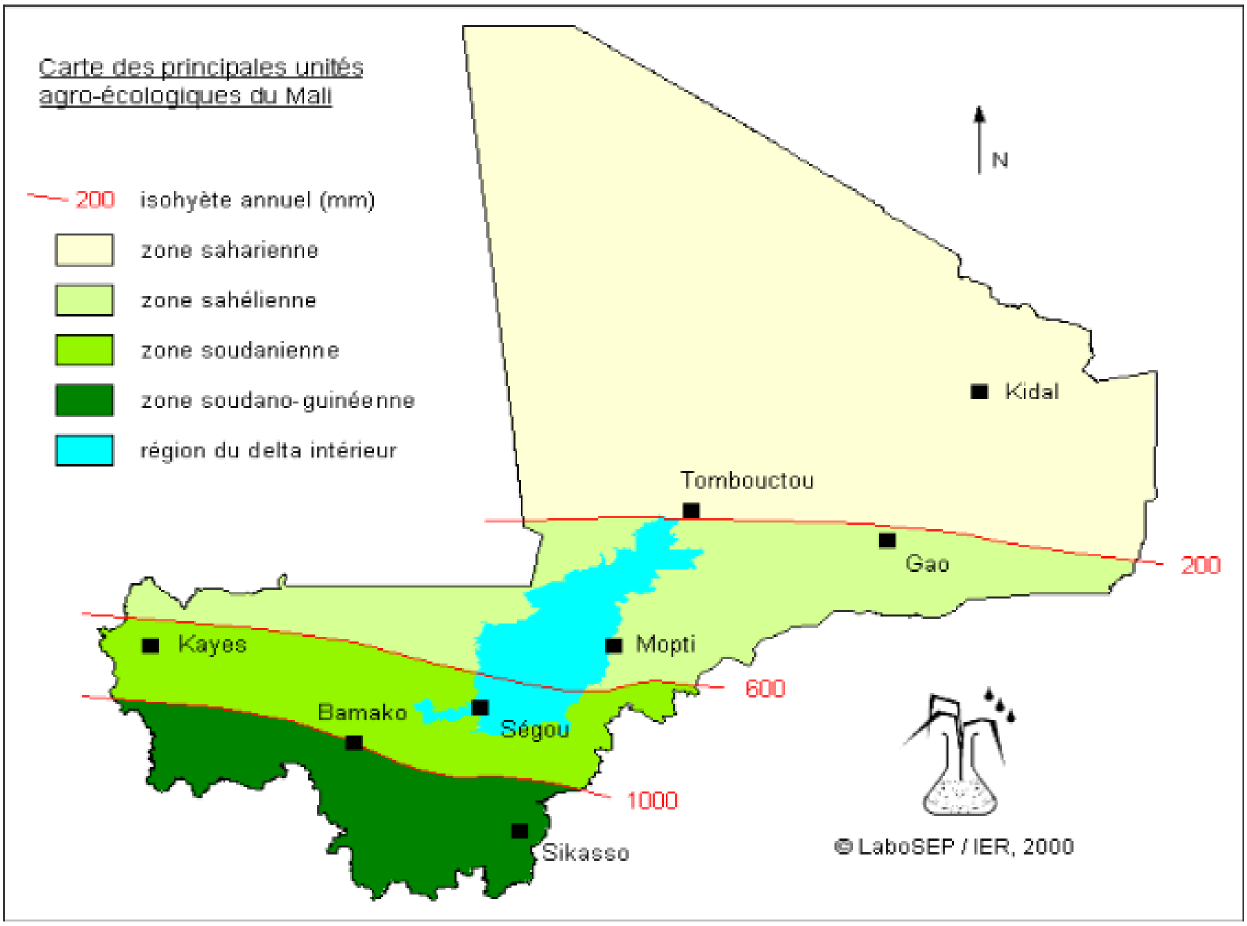


Figure 1: Map of Mali showing agroclimatic zone and mean annual rainfall between 1971 and 2000

Source: Republique du Mali (2007).

2.2. Niger

Niger is facing rapid population growth. In 2012, the population of Niger was estimated 17.1 million, with 51.6 percent of its population being younger than 15 years old. One of the fundamental characteristics of this statistical data is the high population growth rate, estimated as 3.8 percent (World Bank, 2019). Niger's population is expected to double in the next 20 years. The population is unequally distributed on the national territory. Nearly 80 percent of the population lives in rural areas, and 40 percent of the urban population of the country is in the capital Niamey. Irrigation has emerged as a priority in agricultural policy to intensify and secure food production in the face of uncertain climate. This political will was apparent in the early 1960s through the continuation of studies on the development possibilities of the Niger River initiated during the colonial period and the development of large irrigated perimeters.

From the mid-1960s to today, irrigation in Niger developed mainly in four forms, namely 1) Hydro-Agricultural Development (HAD) with total water control, 2) partially controlled Crop Perimeters (PCP), 3) partially controlled Small Private Irrigation (SPI), and 4) Ripple. The country has 15 million ha of agricultural land (11 percent of the total area of the country). The potentially irrigable land is estimated at 270,000 ha, but only 107,000 ha are developed. The irrigation potential is largely determined by the flow of the Niger River, with almost half of the undeveloped potential referring to this river valley. The rest of the country benefits only from sporadic, low flows that are extremely variable from year to year. There are, however, many ponds and shallow underground reservoirs in Niger. One thousand ponds, including 175 permanent and about twenty reservoirs totaling nearly 100 million m^3, are scattered across the national territory. Regarding groundwater, there are two categories: aquifers with high turnover rates and those with very low turnover rates. Aquifers with high turnover rates are mainly located in the southern region of Niger, while those with low turnover rates can be found in the north.

Past programs on irrigation have been successful. In the 1970s, large-scale irrigations were initially introduced intensively; then, irrigation programs gradually moved towards a more integrated approach based on small-scale irrigation supported by the government in the 1980s. Small-scale irrigation has been booming in Niger since the 1990s (Hamidou, 2011). Investments have allowed for the development of an annual increase of about 500 ha of irrigable land. To establish a food security policy of which irrigation is the backbone, the government developed a National Strategy for the Development of Irrigation and Collection of Runoff Water (SNDI/CER) in 2005. This strategy traces the main lines of intervention in large-scale irrigation but does not sufficiently address small-scale irrigation schemes. A specific strategy for small-scale irrigation was initiated in 2015. The Strategy for Small Irrigation in Niger (SPIN) is part of the first program of the 2012 initiative established to achieve food security and sustainable agriculture and sustainable development (Initiative 3N), aiming to unify the strategy of interventions in rural areas. This strategy responds to the need to harmonize interventions and funding approaches in the field of small-scale irrigation and leads to a decentralized mechanism for the development of sustainable demand-driven small-scale irrigation.

Small-scale irrigation is prevalent in three regions: Maradi, Tahoua, and Zinder (Figure 2). The irrigation potential in Maradi is about 30,000 ha. There is an important hydrographic network that cumulates an annual flow of water of 500 million m^3 passing through the valleys. About 70 percent of these valleys are concentrated in Goulbi valley and its tributaries. In Tahoua, the irrigable potential amounts to nearly 35,200 ha, of which 30 percent are developed. The hydrographic network is highly developed, with an annual flow of approximately 400 million m^3 of water. In Zinder, the irrigable potential amounts to 18,000 ha distributed across 1,400 basins, 30 plains, and 300 ponds (20 of which are permanent), totaling 300 million m^3 of water with many facilities. Small-scale irrigation in Niger is mostly practiced using manual dewatering techniques in the traditional catchment basins. To a limited extent, new low-cost technologies, such as drip irrigation, drilling and wells, motor pumps for the dewatering, pedal pumps, traditional sumps, and the California network for distribution, have been disseminated in Tarka valley (Tahoua), Maradi Goulbi, and South Zinder. Smallholders in the water management units are often engaged in the horticultural production of onions, lettuce, tomato, potatoes, squash, pepper. An analysis conducted by the government during the development of the small-scale irrigation strategy showed that small-scale irrigation resulted in an expansion of vegetable production between the 2000s and 2010s (Republic of Niger, Ministry of Agriculture, 2015).

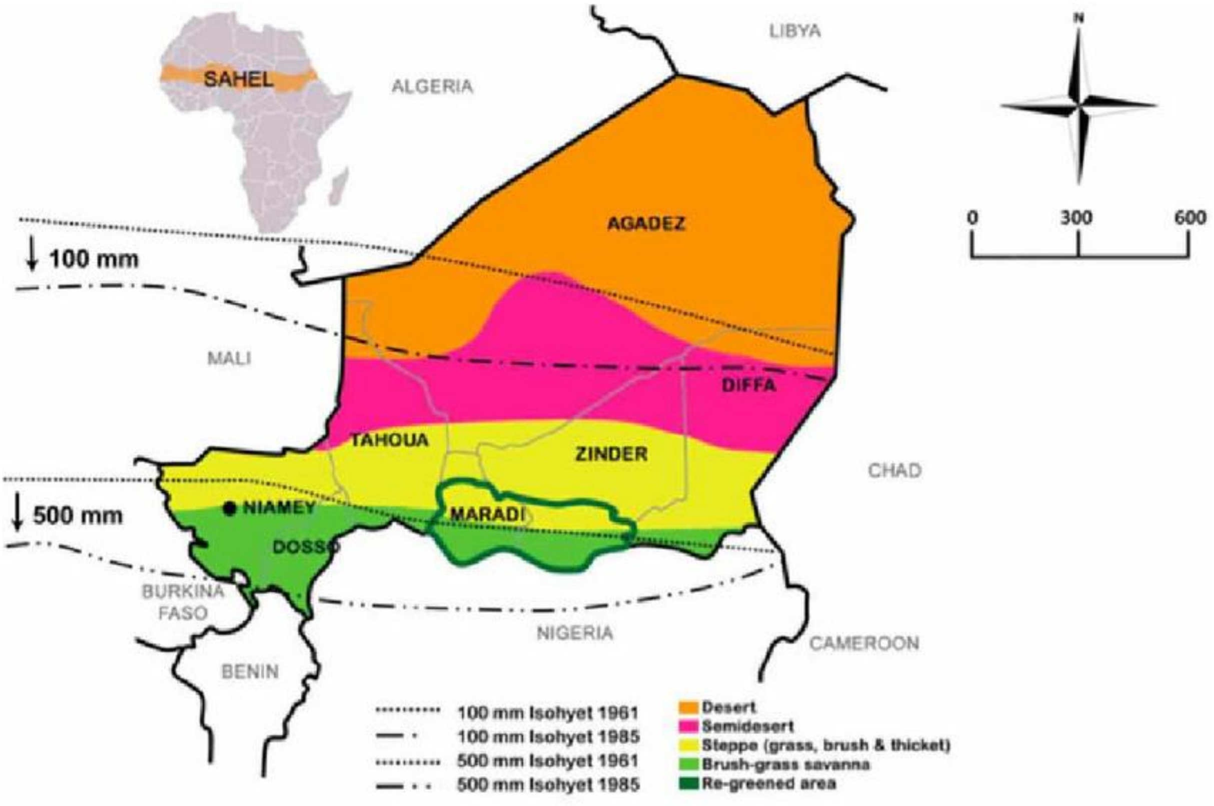


Figure 2: Map of Niger showing agroclimatic zone and rainfall distribution by region

Source: Sendzimir, Reij, and Magnuszewski (2011).

3. Analytical Framework

Given the complexity and site-specificity of small-scale irrigation technologies and its full advantages, there is a need for an analytical approach to systematically assess the potential of small-scale irrigation projects at a local level and for scaling-up to the national level. At the country level in Mali and Niger, we adapted IFPRI's irrigation potential assessment framework (Xie et al., 2018; Xie, You, and Takeshima, 2017; Xie et al., 2014) that integrates several modeling tools and biophysical and socioeconomic data. The analytical framework can help a country identify locations with the greatest investment potential at the national level under joint constraints of the economic viability of irrigated crop production and the suitability and sustainability of the biophysical environment. This section describes the main components of the framework and its implementation in Mali and Niger to provide spatially disaggregated and quantitative estimates of small-scale irrigation development potentials.

The framework developed by IFPRI for national irrigation investment analysis in South Saharan Africa is illustrated in Figure 3. Two main components of the analytical framework are the *Geospatial Suitability Analysis* and the *Agent-based Model*, which is used to simulate the expansion pathways of future irrigated agriculture.

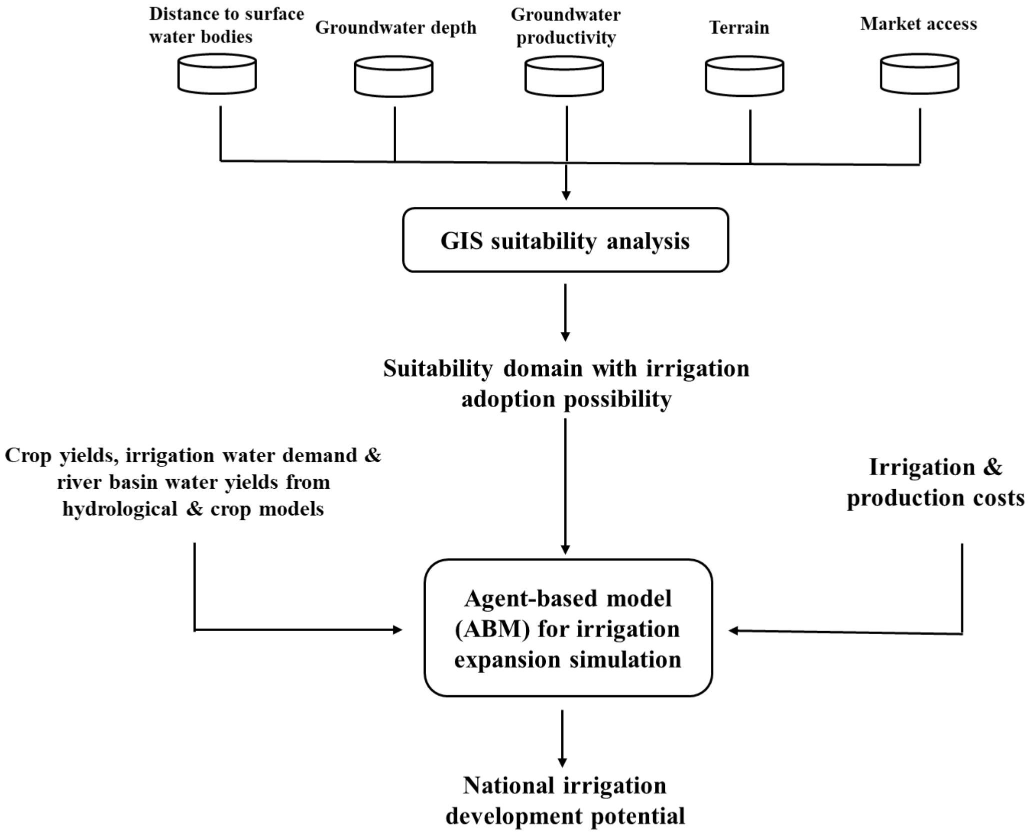


Figure 3: Analytical framework for the assessment of national small-scale irrigation development potential

Source: Authors.

The *Geospatial suitability analysis* uses a series of irrigation-relevant geospatial data layers to assign a spatially explicit land suitability score (i.e., between 0 and 1) for new irrigation development. The land suitability score is then used to establish the suitability domain for small-scale irrigation as an initial estimate of the geographic areas for which small-scale irrigation is suitable. Any number of data layers can be used in this analysis, depending on the characteristics of target areas and the requirement of specific irrigation technology to assess. The layers used in this analysis are selected through a participatory consultation with in-country experts. For the case studies developed for the Program of Accompanying Research for Agricultural Innovation (PARI) in Mali and Niger, five types of data layers were selected from consultative meetings and literature review: 1) distance to surface water bodies, 2) groundwater depth, 3) groundwater productivity, 4) slope or steepness of terrain, and 5) market accessibility. These layers were combined using the Analytical Hierarchy Process (AHP) (Saaty, 1987). This technique effectively reduces the complexity of the multidisciplinary decision to a series of pairwise comparisons (e.g., comparing layers A and B, A is more important than B). For both Mali and Niger, the AHP process led to the synchronized rationale that the slope is of the greatest important for the suitability of small-scale irrigation, followed by groundwater productivity, groundwater depth, market accessibility, and distance to the surface water. Inclusion of market accessibility was considered critical as the intensification of irrigated production entails significant costs (e.g., fertilizers, pesticides, fuel, equipment repair costs) for the producer. Thus, investments in irrigation will only be feasible if production at a remunerative price exists and can be exploited by smallholder farmers adopting irrigation technologies. Market access is also required for equipment and facility maintenance as well as sales of crop products. When combined with appropriate weights, the map of suitability scores gives an initial estimate of the geographic areas in which irrigation adoption could occur (that is, potentially be adopted).

The land suitability layers generated in the *Geospatial suitability analysis* serve as an initial estimate of spatial extent where irrigation adoption could occur, which is refined through the second stage of simulation analysis. In the simulation analysis, we simulate the expansion of small-scale irrigated agriculture with water budget and economic cost-benefit associated with the expanded irrigated production being evaluated explicitly and use the area the expansion can achieve in the simulation as a final estimate of irrigation development potential of the studied countries. Specifically, the following two underlying assumptions are made in the design of the model used in the simulation analysis:

1. Irrigation expansion should be environmentally sustainable. Water availability is a factor that determines adoption. Water availability in this study is determined according to quantity of renewable water resources. Irrigation expansion in a river basin stops if renewable water resources available for irrigation in the river basin are depleted.

2. Irrigation adoption must be economically profitable. Note that continued long-term development of irrigation may result in a surplus of agricultural production, which will lower the market prices of crops. Farmers are assumed to adopt small-scale irrigation until the point where economic profitability vanishes. The price of irrigated crops in our simulation is simulated as an endogenous variable and the long-term economic viability is evaluated in the simulation.

In this study on Mali and Niger, we also made the following key assumptions:

1. Prices of irrigated crops reflect the market demands for these crop products, which in turn are functions of population and income. The irrigation potential discussed in this study is therefore temporally varying. We chose 2030 as a planning horizon. The output from this type of short-term planning analysis is more useful to inform discussion on operational policies than a long-term planning analysis would be.
2. There is conventional wisdom that farmers are more likely to use irrigation to produce high-value crops. Irrigable crops in this study are assumed to be vegetables, pulses, wheat and rice. Mali and Niger have alternating rainy and dry seasons. We consider dry season as a main season of irrigation. That is to say, the irrigation potential is defined as the scale of irrigated production of vegetables, pulses, maize and rice which could be achieved in the dry season under constraints of water availability and economic profitability.

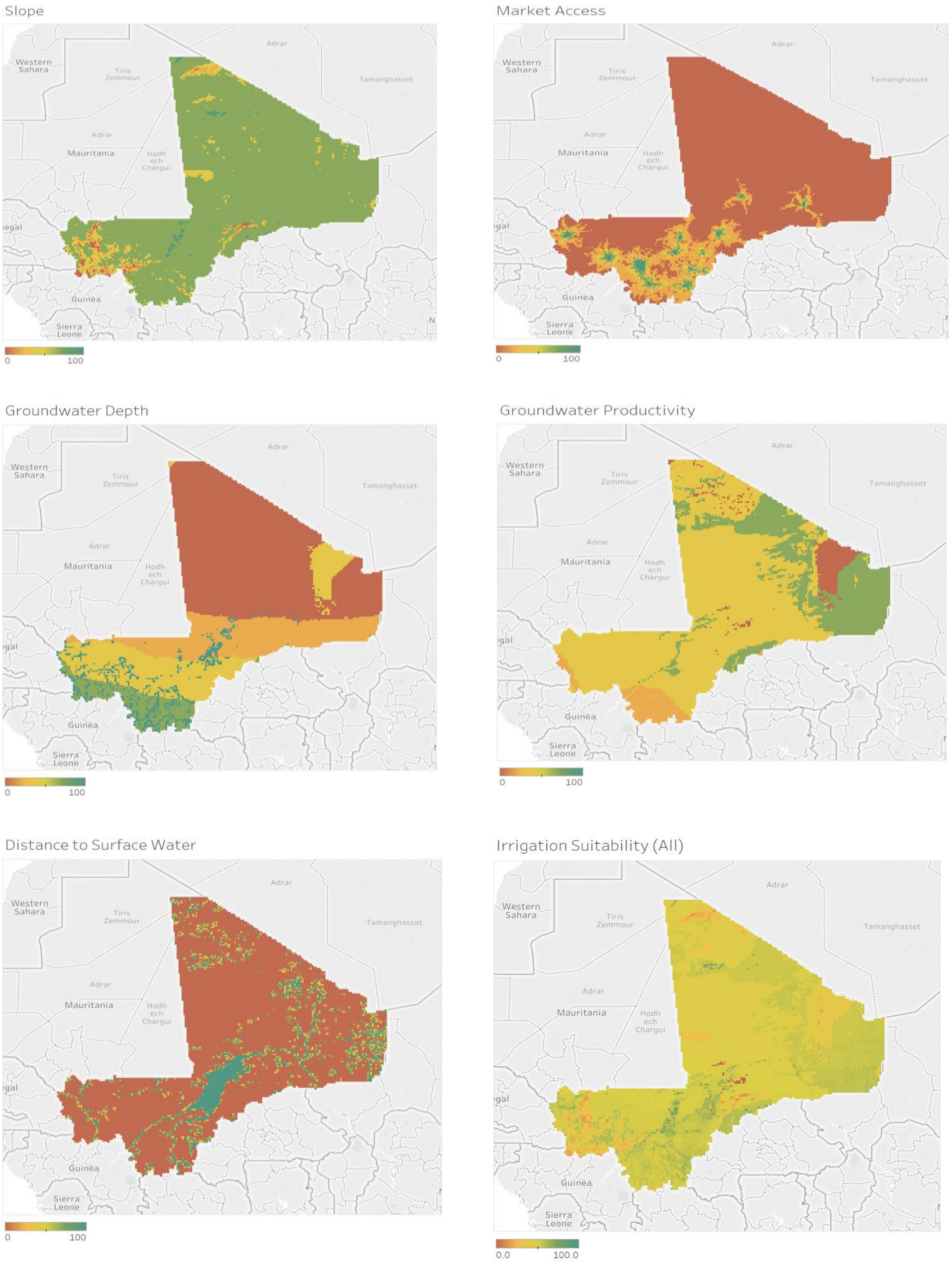
The model used in this second step of simulation analysis reflects the latest development in IFPRI's assessment approach. The model is designed based on the notion of *Agent-based modeling* (ABM) and it is developed to substitute the optimization-based model IFPRI previously used in irrigation planning analyses for Sub-Saharan African countries (Xie et al., 2014; Xie et al., 2017). The optimization-based model identifies the irrigation expansion scheme that maximizes the total profit of the irrigated agricultural sector and takes it as an estimate of the irrigation development potential. The estimated irrigation development potential generated using the optimization model is essentially an outcome of central planning. In reality, small-scale irrigation is a decentralized approach for irrigation development. Agent-based modeling offers a solution to modeling the dynamics of such systems (Berger, 2001; Deffuant et al., 2000) by allowing for defining farmers as autonomous agents, and therefore provides a more realistic representation of real-world decision-making processes behind small-scale irrigation expansion. See Annex A for more details about the Agent-based modeling methology and its implementation in this study.

4. Results

4.1. Mali

The maps of slope, market access, groundwater depth, groundwater productivity, distance to surface water, and irrigation suitability for Mali are shown in Figure 4. The gradient of slope reveals that a significant part of Mali meets the suitability criteria (i.e., slope of less than 5 percent). Only the south-eastern part (Keyes region) is generally marginal or unsuitable in terms of the slope. The result for the market access reveals that more than half of the land in Mali, especially the northern regions comprising Gao, Kidal, and Tombouctou, is unsuitable due to its low market accessibility (i.e., more than 60 minutes of travel time required to reach a market). Market access is largely suitable in the other regions, that is, in Sikasso, Segou, Bamako/Koulikoro, Keyes, and Mopti. The depth of groundwater is an indicator of resilience to climate shocks in Mali. The results underline the high suitability in the southern part of Mali (Sikasso, Segou, Bamako/Koulikoro, Keyes, and Mopti) with 25 m groundwater depth. The results for groundwater productivity reveal that most of the northern region (Tombouctou, Gao, and Kidal) is suitable while some parts of Kidal and Tombouctou are not. Results show that the perennial streamlines are dispersed along with the courses of the Niger River. Generally, there is a substantive distance (above 5 km) to reach perennial streamlines in Mali.

The result of the overall suitability analysis (last panel in Figure 4) confirms the results of the composite index of suitability that combined five criteria (slope, market access, groundwater depth, groundwater productivity, and distance to surface water). The overall suitability analysis reveals no distinct pattern, but spatially dispersed locations of suitability indicating that Mali is generally suitable for small-scale irrigation. Slope, groundwater productivity, and distance to surface water seem to constitute the three major criteria driving the suitability of irrigation in Mali. However, this result is based on the country's natural endowment and does not account for potential innovations and technologies to curtail the natural constraints substantially. For example, groundwater depth can be overcome by appropriate drilling technology. This situation would lead to incurring additional costs that may not be affordable for individual smallholders except for cases of resource-pooling by groups of farmers.



Slope

Market Access

Groundwater Depth

Groundwater Productivity

Distance to Surface Water

Irrigation Suitability (All)

Figure 4: Reclassification maps for slope, market access, groundwater depth, groundwater productivity, distance to surface water, and irrigation suitability in Mali derived through the GIS-based Multi-Criteria Evaluation technique.

Note: Scales are normalized to 0-100, where 0 and 100 represent the most unsuitable and suitable, respectively, for each criterion.
Source: Authors.

The disaggregation of the results for the irrigation suitability and potential cropland area by region and the administrative unit is presented in Figure 5. The results show that the most promising regions for investment in small-scale irrigation projects are in Segou, Sikasso, Mopti, Koulikoro, and Keyes. The administrative units in Segou with more than 10,000 ha of cropland potentially suitable for irrigation are Segou, Bla, San, Niono, Baroueli, and Macina. Similarly, the administrative units of Koutiala, Sikasso, Yorosso, Kadiolo, and Kolodieba in Sikasso have more than 10,000 ha of cropland each which is potentially suitable for irrigation. There are only two administrative units in Mopti that have more than 10,000 ha of cropland each, which is potentially suitable for irrigation, Mopti and Djenne. In the administrative unit of Koulikoro, Dioila, Kati, Koulikoro, and Kangaba are potentially suitable for irrigation with 10,000 ha of cropland area each. Only one administrative unit in Keyes has more than 10,000 ha of cropland that is potentially suitable for irrigation. There are no administrative units with more than 10,000 ha of cropland, which are potentially suitable for irrigation, in Gao and Bamako.

Overall, Segou, Sikasso, and Mopti are the three most important regions with irrigation suitability by cropland area in Mali. These regions have most of the administrative units with over 30,000 ha of cropland area, including Segou, Bla, San Niono, and Barroueli in Segou. The administrative units with over 30,000 ha of cropland area in Sikasso are Koutiala, Sikasso, Yorosso, and Kadiolo. Mopti and Djenne of Mopti administrative units have over 30,000 ha of cropland area each.

The results show that the likelihood of irrigation adoption is higher in the southern part of the country than in the northern part. The location covers five out of the eight regions in Mali. The regions with a high probability of adoption of small-scale irrigation are Sikasso, Koulikoro, Kayes, Segou, and Mopti (see Figures 6 and 7). These administrative regions represent 81 percent of the country's population. Similarly, the regions of Sikasso, Koulikoro, Kayes, Segou, and Mopti show the level of water scarcity induced by irrigation development in Mali. Hence, the availability of water (especially rivers and dams) is a driver for the adoption of irrigation in Mali. Although earlier results showed that high irrigation suitability occurs in the north-eastern part of the country, the result for the probability of adoption indicate that the likelihood of irrigation adoption is high in the southern part of the country. This result underscores the importance of profitability as critical in determining irrigation investment in Mali.

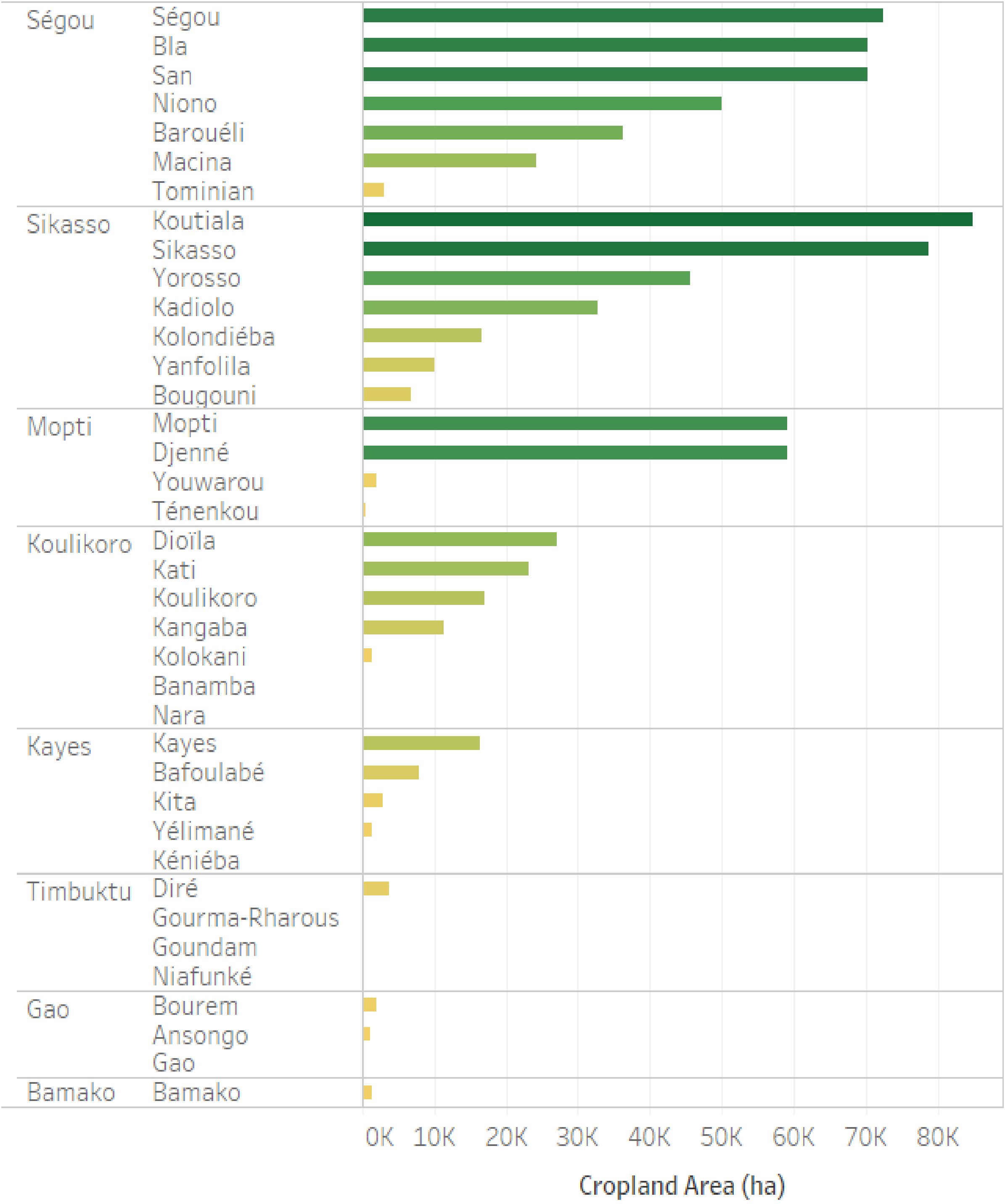


Figure 5: Irrigation suitability by region and administrative units in Mali

Source: Authors.

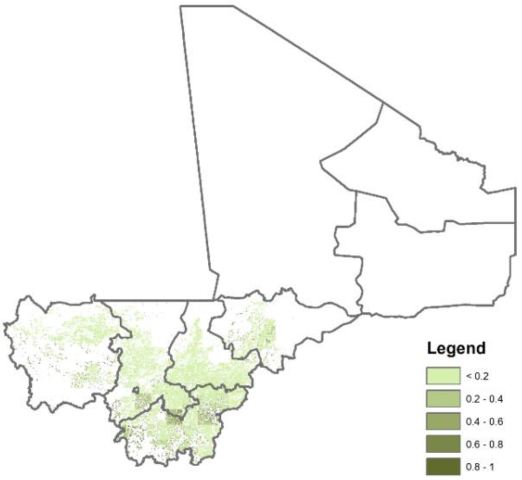


Figure 6: Adoption probability of irrigation in Mali

Source: Authors.

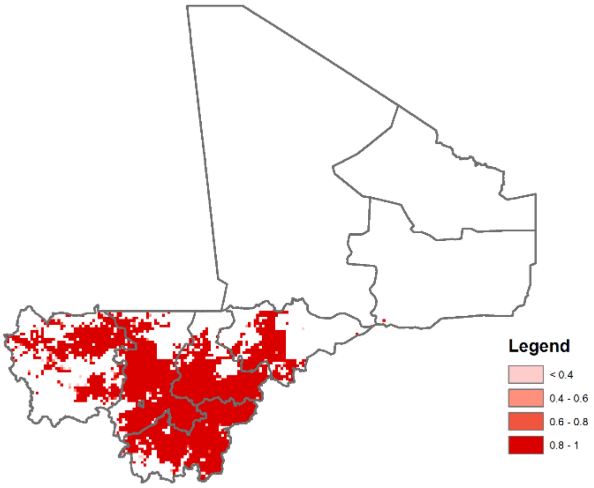


Figure 7: **Probability of water scarcity induced by irrigation development in Mali**

Source: Authors.

Further, results on the expected adoption potential (coverage by land area) of irrigation and profits from the adoption of irrigation in Mali reveal five major regions with a high potential of adoption of irrigation: Sikasso, Koulikoro, Segou, Kayes, and Mopti. For instance, in Sikasso, 49 percent of the land are suitable for irrigation and the region accounts for 47 percent of the total expected profits. In Koulikoro, 19 percent of the land area has irrigation potential, but the region has a proportionally higher share of the total expected profit of 22 percent. Interestingly, although Kayes has a higher land area for the adoption of irrigation than Segou, the share of the expected profit of Segou (14 percent) is higher than that of Kayes (11 percent). This disproportionality in expected profit (vis à vis land area) is due to the value of the agricultural commodity under the irrigation system and land productivity (yield gap). Overall, only three regions (Sikasso, Koulikoro, and Segou) accounted for 83 percent of the total expected profits on irrigation in Mali. These three regions are, therefore, potential regions for the development of irrigated agriculture in Mali.

4.2. Niger

The reclassification maps for small-scale irrigation suitability, slope, distance to surface water, groundwater depth, groundwater productivity, and market access are shown in Figure 8. The results indicate that most of Niger's territory has a highly suitable slope (of less than 5 percent). Some more hilly land is in the north of the country around the Aïr plateau. Following these criteria, irrigation is likely to occur in many areas. The maps also reflect that groundwater productivity is not a limiting factor for small-scale irrigation in Niger. In large parts of the country, groundwater productivity is greater than 1l/s. The productivity of groundwater is very high in the south, north-west, and north-east (superior to 20l/s). The lowest productivity is found in Aïr and in the south of Tillabéri. On the market access map, the predominantly red areas indicate that these criteria can be a constraint in developing suitable small-scale irrigation. The results show that the travel time to urban markets exceeds 180 minutes in most areas. This result is not surprising since most of the markets are concentrated in the south-eastern part of the country.

Regarding the criterion of depth of groundwater, the shallow phreatic aquifers are in the south band (Ader-Doutchi-Maggia, Dallols Bosso, Maouri, Foga, and the Komadougou valley). The moderately deep aquifers (between 10 m and 50 m) are found on the east-west band. In the Saharan zone (65 percent of the territory), the water resources are not easily accessible since the depth of the phreatic water exceeds 50 m.

Access to surface water in Niger is facilitated by the remarkable volume of surface flow of water. These surface water resources belong to two systems: the Niger River basin in the west and the Lake Chad Basin in the east. They are divided into seven hydrological units: the Niger River and its tributaries, Ader Doutchi Maggia, Goulbis, Koromas, the Komadougou Yobe, and the basin of Lake Chad, the koris of Aïr, the Tarka. Also, there are many pools, including 175 permanent and several reservoirs of surface water. Unfortunately, these water sources are unevenly distributed, and several localities are more than 5 km from a potential water source.

Finally, by combining all criteria, the AHP analysis shows that globally Niger's land is almost suitable for irrigation. The overall score for land suitability for irrigation development is greater than 50. This result indicates an average ability to the irrigation. Some green areas with a highly suitable slope (Figure 8) in the arid parts of the north or east of the country do not have suitable groundwater depth.

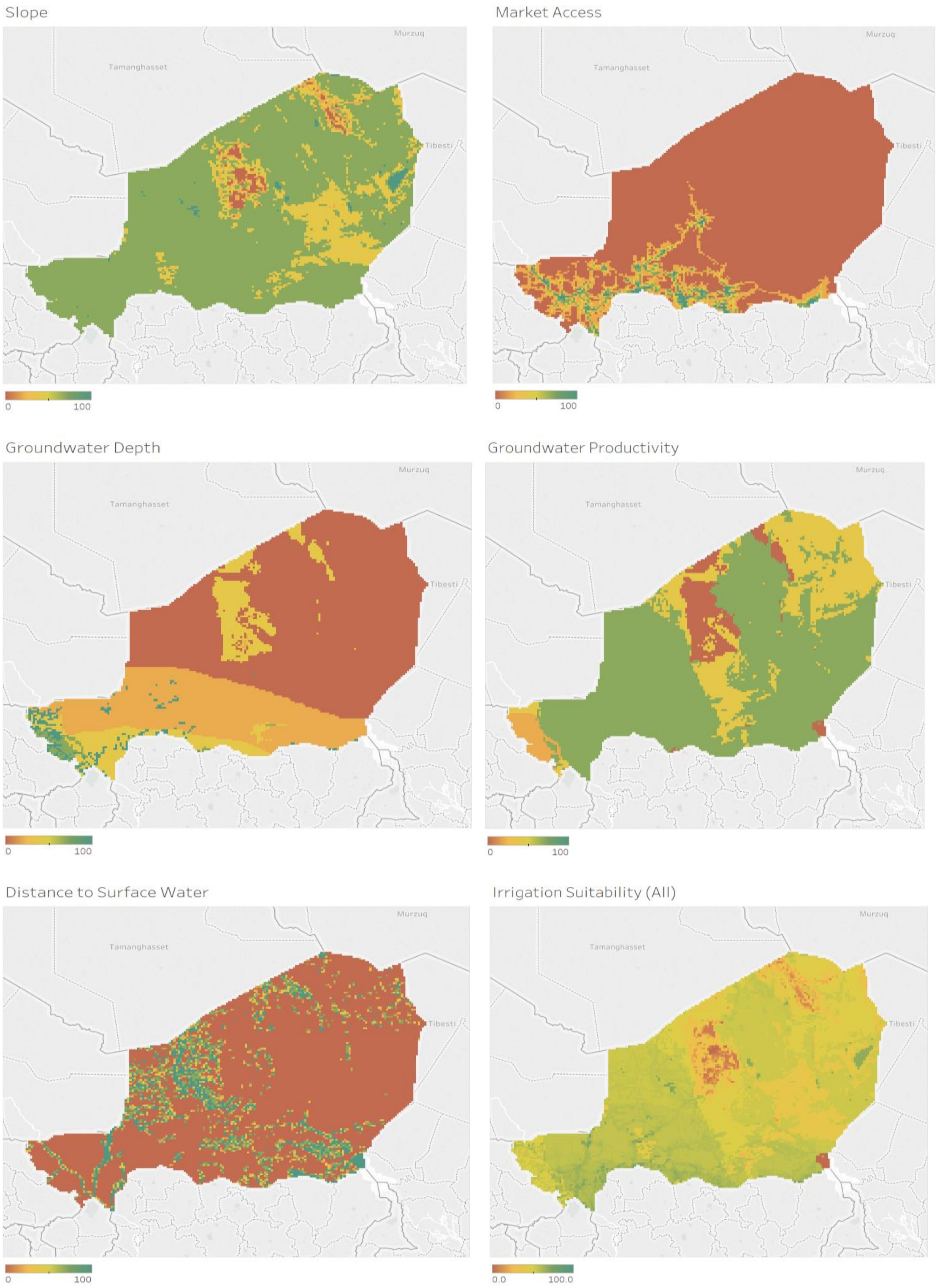


Figure 8: Reclassification maps for slope, market access, groundwater depth, groundwater productivity, distance to surface water, and irrigation suitability in Niger derived through the GIS-based Multi-Criteria Evaluation technique

Note: A score equal to 0 indicates a lack of irrigation suitability, while the score 100 indicates perfect irrigation suitability. The suitability score is a numerical value indicating a location's overall suitability for given land use when all of the suitability factors are considered.

Source: Authors.

The disaggregation of the results of the status of irrigation suitability by region and the administrative unit is presented in Figure 9 and indicates relatively large disparities within local areas. Regions most likely to develop suitable irrigation are Zinder, Dosso, and Tillaberi. These regions indeed have a significant potential for small-scale irrigation. The potential irrigation area in Zinder is about 18,000 ha, distributed over 1,400 basins, 30 plains, and 300 ponds (including 20 permanent ones), totaling 300 million m^3 of water with numerous facilities. Temporary rivers feed these aquifers and ponds. In Tillaberi, the potentially easily irrigable area amounts to 50,000 ha, which may be expanded to reach 120,000 ha, given a deep-water table of up to 20 m depth. We found that Zinder has the highest score or index of cropland areas suitable for irrigation, including the departments of Tanout, Mirriah, and Magaria. It is followed by Dosso, specifically the three departments of Dogon Doutchi, Boboye, and Gaya. In Tillabéri, the department of Fillingue appears the most suitable.

This section presents the results of agent-based modeling for the upscaling of small-scale irrigation technology in Niger. As demonstrated in the map, there are a few zones in which successful adoption could most likely be expanded, specifically the Niger river Valley and areas close to the Lake Chad. Note that even in these zones, the probability is under 20 percent. This result means that, although Niger's land suitability to irrigation spread over the most part of the country, the expansion of profitable irrigation is unlikely in the north and south-east of the country. This result indicates that the economic viability of small-scale irrigation is weak, as the risk of water scarcity is high. The weak probability in the southern zone can be explained by the lack of dams to retain water all-year-round and maintain water depth. There is, however, a high potential for shallow water irrigation and longer-length growing seasons for rainfed agriculture.

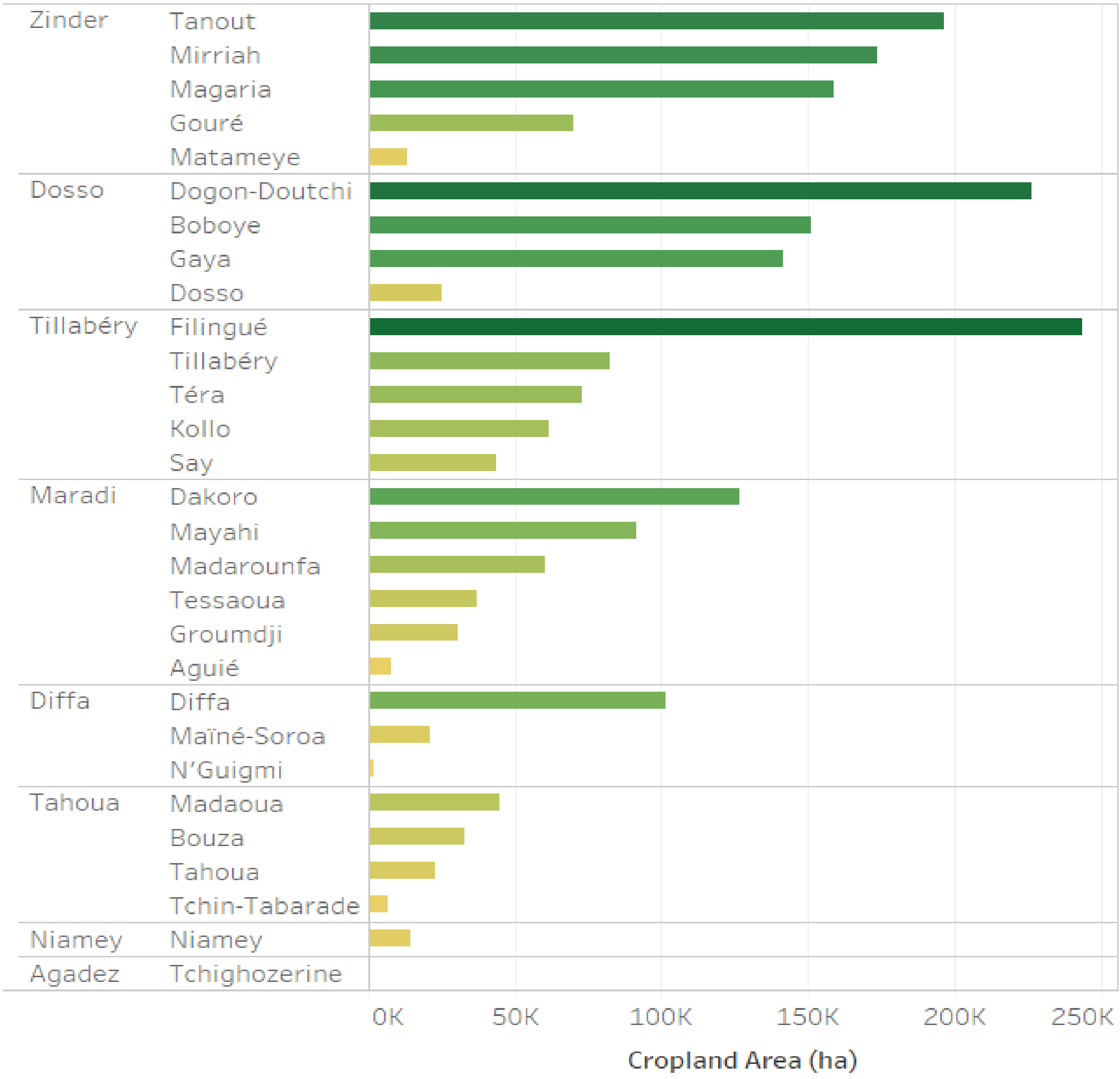


Figure 9: Irrigation suitable cropland area aggregated by administrative units in Niger

Source: Authors.

Unfortunately, regions where small-scale irrigation is most likely to occur have a high risk of water scarcity associated with expansion (Figures 10 and 11). This high risk is found in over 80 percent of the land area in question, as shown on the map (Figure 11). This result can be linked to the permanent unavailability of water due to seasonal climatic conditions. In these regions, it is important to reduce the negative environmental and socioeconomic consequences of small-scale irrigation development. Hence, small-scale irrigation investment activities must be accompanied by appropriate institutional arrangements, incentives, and regulations.

The simulations indicate that the expected development potential of small-scale irrigation in Niger is about 95,700 ha, located mainly in Tillabéri, Dosso, and Maradi. These three regions account for more than 90 percent of the expected irrigation potential in Niger. Tillabéri appears as the state with the largest potential (over 50,000 ha), and an expected profit of more than 80 million USD/year. In Maradi, where the expected adoption potential refers to about 15,000 ha, the expected profit seemed to be the weakest compared to the other regions. This analysis of the expected profit highlights the importance of developing low-cost, small-scale irrigation technologies to maximize the expected profit.

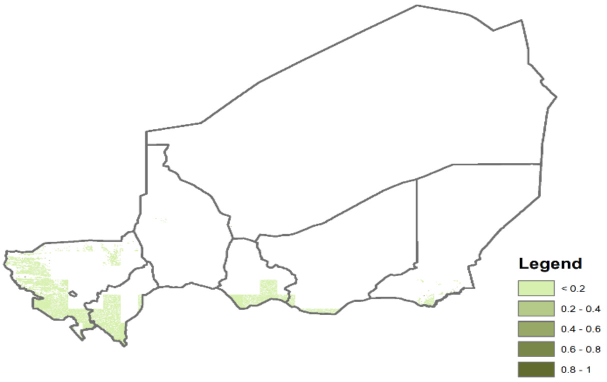


Figure 10: Adoption probability of small-scale irrigation in Niger

Source: Authors.

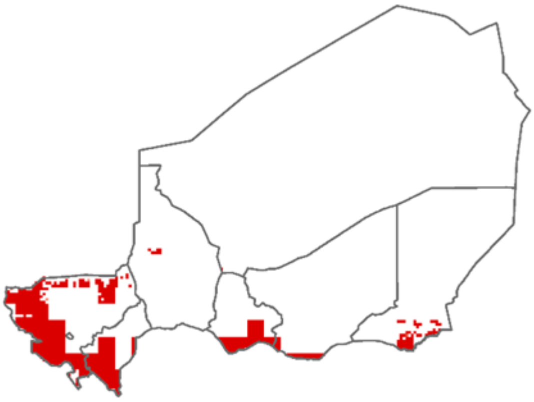


Figure 11: Probability of water scarcity induced by irrigation development in Niger

Source: Authors.

5. Discussion

This study investigated the potential of small-scale irrigation in smallholders' agriculture in Mali and Niger, using high-resolution geospatial analysis and agent-based modeling approaches. Information on irrigation suitability at a spatially disaggregated level provided a new research opportunity for assessing small-scale irrigation investment planning and strategic site selection. Large shares of cropland in both countries are rainfed under the arid and semi-arid climate conditions, and they are particularly more vulnerable to climate change and extremes being projected in the future. Wherever found suitable, results from this study were encouraging that the potential benefits from the adoption of small-scale irrigation outweigh the cost and risk of investments. Small-scale irrigation in areas with high suitability can yield higher income, reduce poverty, and reduce vulnerability to climate shocks. This finding aligns with previous studies that showed the critical role of small-scale irrigation in preventing on-farm income losses during periodic droughts and enhancing smallholders' resilience through multiple cropping seasons (e.g., Hamidou, 2011; Sendzimir et al., 2011).

5.1. Findings in Mali

Results have shown that irrigation suitability in Mali is mostly driven by slope, groundwater productivity, and distance to surface water. These factors should inform policymakers of the appropriate locations for small-scale irrigation projects. The findings of this study also suggest that the government should prioritize the development of surface water systems (e.g., river networks, inland valley basements, lowlands, ponds, micro-dams, and water harvesting systems) to unlock the potential of small-scale irrigation. Since not all administrative units of the country are found suitable for small-scale irrigation, targeting and scaling up of small-scale irrigation should be focused on in highly suitable locations. Specifically, we propose the next revision of the National Strategy for the Development of Irrigation (NSDI) to incorporate the findings of this spatial specificity as evidence for prioritizing support for small-scale irrigation systems in the identified suitable areas. For example, the strategy can cluster small regions of high suitability into the zone of small-scale irrigation development to promote scalable adoption. Five such clusters with a high potential of adopting small-scale irrigation identified in this study are in Sikasso, Koulikoro, Segou, Kayes, and Mopti. Policies on land use and water use rights will be complementary to prevent potential conflicts in water allocation.

5.2. Findings in Niger

Results from the suitability mapping analysis indicated that the potential for sustainable small-scale irrigation expansion in Niger is relatively high across regions. However, when economic factors were considered using agent-based modeling, there were only a few zones in which adoption would be highly likely to occur. This result highlights the importance of capital and operational costs (e.g., costs for water-lifting technology, fuel, agricultural input, and labor) for the success of small-scale irrigation investments in Niger. It becomes evident that most of the suitable areas for small-scale irrigation have high operational costs. The low asset base of most farmers and associated funding constraints reduce their capacity to adopt small-scale irrigation.

The zones where the adoption of small-scale irrigation could occur are in the Niger River Valley and in areas close to Lake Chad. These zones are, however, associated with a high risk of water scarcity. This characteristic is consistent with the slim probability of adoption. Therefore, an expansion of irrigation in these areas must be associated with technologies that control water wastage through, for example, the promotion of water-saving technologies, efficiency in water management, and monitoring of aquifers. The modest profit from the adoption of small-scale irrigation in many regions not only stems from the high cost of irrigation schemes but can also come from the high intra-annual variability of price. Price fluctuation is common in Niger and is caused by a lack of storage and processing capacity. These results imply that a provision of complementary services is needed to achieve the objective of productivity improvement.

Overall, we find that the expansion potential for small-scale irrigation in Niger is low and unlikely profitable even in biophysically suitable areas. The risk of water scarcity may be too high if irrigation is expanded.

6. Conclusion and policy implications

Based on the findings, we conclude this study with the following policy implications. First, the suitability of small-scale irrigation needs to be considered in systematic development policy. Even if environmental factors are the major determinants of the occurrence of any irrigation scheme, taking into account economic and social factors is necessary to ensure a suitable small-scale irrigation expansion in the long run. Second, there is a need for better targeting: small-scale irrigation may not be the most promising investment for smallholder farmers in certain locations given the costs and complexity of the technology. Knowledge in areas where the adoption of small-scale irrigation is most likely to occur would allow an efficient use of scarce resources. The spatially explicit suitability information will help avoid financing unsustainable investment projects with low sustainability prospects and low return on investment. The analysis result from this study suggests the promotion of small-scale irrigation in Sikasso in Mali and Tillabéri in Niger. Third, for a sustainable expansion of small-scale irrigation, the costs should be kept very low. Institutional arrangements or strategies should be in place to reduce the cost related to the implementation of small-scale irrigation. Also, an arrangement to improve market access should focus on investing in infrastructure and market monitoring to prevent a possible saturation of produces. Indeed, given the dietary habits of consumers in Mali and Niger and the weak asset base of most farmers in the region, small-scale irrigation will be viable only if the increased yields can be readily marketed. Therefore, infrastructure reinforcing trading channels and increasing storage capacities must be improved. Fourth, it is important to consider the preservation and monitoring of natural resources. As water is one of the limiting factors in the expansion of irrigation, the implementation of a framework of water-saving technologies and groundwater monitoring can help preserve and manage this resource. Policy and regulations concerning water use and water pricings should be favorable for irrigation development but also promote environmental protection.

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Annex A: Methodology of agent-based modeling

The agent-based model applied in this study is described using the ODD (Overview, Design concepts, and Details) protocol (Grimm et al., 2006). The program of the model is written in C++ language.

Purpose

The model is designed to simulate the expansion of small-scale irrigation in Sub-Saharan African countries.

Entities, state variables, and scales

The model includes only one type of agents referred to as farms where irrigation may occur. Farm attribute variables are listed in the following table (Table A1).

Table A1: Farm attributes

Attribute variable	Description
A	Farm size (ha)
w	Annual irrigation water use intensity (m^3 H_2O/ha)
y	Farm productivity, characterized by attainable yield of irrigable crops
S	Suitability score for irrigation adoption of the farm

Due to a lack of data on the spatial distribution of farm sizes, farms in this study are defined on an abstract agricultural landscape or on a grid of 1 km by 1 km. Farm size is defined as existing rainfed cropland area in each 1 km pixel, which is derived from spatial data on the extension of cropland (Fritz, 2015) and downscaled national statistics on agricultural production provided by the Spatial Production Allocation Model (SPAM) (You et al., 2014).

The intensity of irrigation water use during the dry season and the attainable yield of irrigable crops are estimated using the crop simulation module in SWAT (Soil and Water Assessment Tool) (Arnold et al., 2012).

Suitability scores for irrigation adoption of a farm is derived from geospatial suitability analysis.

Process overview and scheduling

A time step in the simulation represents a growing season. At the beginning of each growing season, the adoption decision is first assessed for each non-adopting farm under bounded rationality. The consequence of the adoption is evaluated at the end of each growing season. Prices of irrigated crops are modeled as endogenous variables, and end-of-season prices are estimated according to the production of irrigated crops under the new adoption regime.

"Actual" net income is estimated for each g farm which adopted irrigation using the updated end-of-season crop prices. Farms leave irrigation if the accumulated assets are <0. The model is run until adoption of irrigation achieves a saturation level. Irrigation expansion stops if the renewable water resources available for irrigation are depleted and prices of irrigated crops drop to a level which starts to make irrigated crop production unprofitable.

Design concepts

Basic principles

The model was developed to substitute the optimization-based model IFPRI had previously used in irrigation planning analysis for Sub-Saharan African countries (Xie et al., 2014; Xie et al., 2017), in which the development of small-scale irrigation is essentially viewed as outcome of central planning. In reality, small-scale irrigation is a decentralized approach for irrigation development. Agent-based modeling offers a solution to modeling the dynamics of small-scale irrigation development in a more realistic way.

Emergence

The model reports the adoption probability of small-scale irrigation at farm level and the risk of water scarcity which may arise from the expansion of irrigated production at basin level. There is a stochastic element in the model. The model is executed multiple times to generate multiple realizations of irrigation expansion pathways. The adoption probability p is calculated as

$$p = \frac{n_{adopt}}{N} \tag{1}$$

where n_{adopt} is the number of realizations in which irrigation adoption occurs and N is the total number of realizations.

The water scarcity risk wr is calculated as

$$wr = \frac{n_{wr}}{N} \tag{1}$$

where n_{wr} is the number of realizations in which water availability in the basin becomes binding, and N is the total number of realizations.

Sensing

Farmers have knowledge of crop prices of past years, of the quantity of renewable water resources in the basin and irrigation water use of other adoptive farms, which they use to form the expectations on crop prices and water availability in the coming growing season.

Interaction

The model is designed to capture the interactions between farmers in their decisions to adopt irrigation caused by competition for renewable water resources and the market share of irrigated crops. Social networks and social learning may play a role in irrigation technology adoption. These interactions are not simulated in this study due to the lack of data required to support the simulation of these interactions at a national scale.

Collectives

In the real world, farmers may work as a group such as by forming water user associations. Such collective behavior is not included in the simulation of this study due to the same reason that applies for data on water scarcity.

Stochasticity

In the model, a probability is calculated to represent the influence of environmental suitability on famers' irrigation decisions (see equation AS-3 in submodel AS1), and famers' adoption decisions are made based on this probability.

Initialization

Asset of all farms at the beginning of the simulation are set to zero.

Input data

The input data variable is listed in Table A2.

Table A2: Input data variable

Variable	Description
WY	Annual renewable water resources in basin available for irrigation (m^3 H_2O)

There is very high temporal variability in the generation of renewable water resources within a year. The amount of renewable water resources available for dry-season irrigation is largely dependent on the storage capacity of water infrastructure. In case there is a lack of data to determine the storage capacity the water infrastructure may have, the renewable water resources available for irrigation are set to the total quantity of renewable water resources generated in dry-season months and are estimated using the hydrological simulation module of the SWAT model on a 10 km by 10 km grid. Pixels on the 10 km grid are used as spatial units for water budget evaluation and, to facilitate the discussion, are referred to as "basins".

Submodels

The model contains two sub-models. The sub-model AS1 assesses the probability that a non-adoptive farmer decides to adopt small-scale irrigation at the beginning of each growing season. The second sub-model AS2 simulates the change in crop price under the influence of irrigation adoption. Parameters/variables of these sub-models are listed in Tables A3 and A4.

Table A3: Parameters/variables of submodel AS1

Parameters/variables	Description
WAI	Water resources available for irrigation under farmers' perception (m^3 H_2O/yr)
NP	Annual profit per hectare a farmer may receive from adopted irrigated production (USD/ha)
p_c^e	Farmer's expectation on price of irrigated crop *c* at the beginning of growing season (USD/ton)
C_{irr}	Annual irrigation cost (USD/ha)
C_{other}	Annual non-irrigation-related production cost (USD/ha)
P_{adopt}	Adoption probability calculated to represent influence of environmental suitability on farmers' irrigation adoption decision (0 -1)
$S_{threhsold}$	A threshold of the environmental suitability score for irrigation adoption to occur (0 – 100)
p_{max}	Adoption probability when environmental suitability is 100

Tab A4: Parameters/variables of submodel AS2

Parameters/variables	Description
P_{crt}	Price of crop *c* in market *r* in year *t* (USD/ton)
γ	Intercept of linear demand function
δ	Slope of linear demand function
Q_{cr0}	Production of crop *c* in market *r* in base year (*t*=0) (ton)
ΔQ_{rt}	The increased irrigated production of crop *c* in year *t* (ton)
v_r	Market margin

Sub-model AS1

In the pre-season decision making, farmers first evaluate the water availability and on-farm cost benefit of future irrigated production under bounded rationality.

The amount of water resources available for irrigation under farmers' perception *WAI* is calculated as

$$WAI = WY - \sum_i w_{i,c} \cdot A_i \tag{AS1-1}$$

where WAI are the annual water resources available for irrigation under farmers' perception (m^3 H_2O); WY is the annual amount of renewable water resources available for irrigation in the hosting basin (m^3 H_2O); w is the annual irrigation water use intensity of a farm (m^3H_2O/ha), and A is the farm size (ha). Subscript *i* and *c* are added to the farm size variable A and the irrigation water use intensity variable w and denote those farms where irrigation adoption has occurred and the irrigated crop, respectively.

The on-farm economic cost benefit of irrigation adoption is evaluated as

$$NP = max_c(p_c^e \cdot y_c - C_{irr} - C_{other}) \tag{AS1-2}$$

where NP is the annual profit per hectare a farmer may receive from adopting irrigated production (USD/ha); p_c^e is a farmer's expectation on the price of irrigated crop c at the beginning of the growing season (USD/ton); C_{irr} is the annual irrigation cost (USD/ha), and C_{other} is the annual non-irrigation-related production cost (USD/ha). The price expectation p_c^e is formed using the "actual" price at the end of the last growing season; the non-irrigation-related cost C_{other} is estimated using a profit margin approach or is assumed to be 20 percent of the revenue; the annual irrigation cost C_{irr} is assumed to be USD200/ha. This cost level was chosen to reflect the costs associated with the purchase and operation of water lifting devices such as motor pumps. Note that the maximum is taken over all the irrigable crops. Moreover, once irrigation is adopted, it is assumed that farmers will cultivate the irrigable crop that is most profitable.

$WAI > 0$ and $NP > 0$ are taken as necessary conditions for the adoption of irrigation to occur. The adoption decision is also under influence of environmental suitability. A probability is calculated to represent the influence of environmental suitability on famers' irrigation decisions.

$$P_{adopt} = \frac{p_{max}}{100 - S_{threshold}} \cdot (S - S_{threhsold}) \tag{AS1-3}$$

where P_{adopt} is the adoption probability calculated to represent the influence of environmental suitability on farmers' irrigation adoption decision (0-1); S is the environmental suitability score derived from the geospatial suitability analysis (0-100); $S_{threhsold}$ is a threshold of the environmental suitability score for the irrigation adoption to occur (0 – 100), and $p_{max}$is the adoption probability when the environmental suitability is 100.

In this study, $S_{threhsold}$ is set to zero or we assume that the adoption probability is proportional to the environmental suitability score. It is recommended that a "sufficiently" small value of p_{max} is chosen in simulation to avoid the risk of "over adoption" or prematurity of convergence. When "sufficiently" small values of p_{max} are used, the simulation will converge to the same level of adoption.

Sub-model 2

The sub-model that is used to simulate the crop price change under the influence of irrigation adoption is modified from the Dynamic Research Evaluation for Management (DREAM) model (Wood and You, 2001). The generic structure of the sub-model is described below:

The sub-model is a partial equilibrium multi-market model. For each regional market, the price-consumption quantity relationship for irrigable crop c is represented by a linear demand function:

$$c_{crt} = \gamma_{cr} + \delta_{cr} p_{crt} \quad \text{(AS2-1)}$$

where subscript r denotes the regional market; subscript t denotes the time step or growing season in the simulation; c_{crt} is the quantity of annual consumption of crop *c* in market *r* in year t (ton); p_{crt} is the price of crop *c* in market *r* in year t (USD/ton), γ_{cr} is the intercept parameter of the linear demand function for crop *c* and market *r*, and δ_{cr} is the slope parameter of the linear demand function for crop *c* and market *r*.

The price of crop *c* in the regional market *r* is calculated as

$$p_{crt} = \frac{\sum_r (Q_{cr0} + \Delta Q_{rt}) - \sum_r \gamma_{cr}}{\sum_r \delta_{cr}(1+v_r)} \cdot (1 + v_r) \quad \text{(AS2-2)}$$

where Q_{cr0} is the production of crop *c* in market *r* in the base year (*t*=0) (ton), ΔQ_{rt} is the increased irrigated production of crop *c* in year *t* (ton) and v_r is the market margin.

Note that the population and income growth may shift demand functions. These dynamics are not simulated in our model explicitly. Values of the intercept and the slope parameter of the demand functions that represent the price-consumption relationship at the end year of the planning period (2030 in this study) should be chosen in the simulation. Increased irrigated production in year t ΔQ_{rt} is calculated by summing all increased irrigated production (=farm size x attainable yield under irrigation) over all adoptive farms in the regional market in that year.

In this study, due to lack of data at sub-national level, only one national market is defined. The data used to parameterize submodel AS2 (e.g. on crop production/consumption and price in the base year and projected population and growth rates by 2030 in two study countries) are obtained from FAOSTAT and the IFPRI IMPACT modeling system (Robinson et al., 2012).

At the end of each growing season, the profits that famers “actually” received are calculated using equation AS1-2 as well by substituting “actual” prices estimated by submodel AS-2 for expected prices p_c^e.