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Invest in small-scale irrigated agriculture: A national assessment on potential to expand small-scale irrigation in Nigeria

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ABSTRACT

Nigeria is faced with the daunting challenge to improve performance of its agriculture sector. Currently, crop production in Nigeria is predominantly rainfed; irrigation is perceived as an important means to boost agricultural productivity in the country. We estimated the potential of expanding small-scale irrigation in Nigeria, considering both biophysical and economic constraints. Under baseline conditions, the land area in Nigeria with investment potential for small-scale irrigation is estimated to be 1 million ha in dry-season and 0.65 million ha in rainy season, respectively. Further sensitivity analyses show that the estimated potentially irrigable area depends on input parameters such as irrigation cost, fertilizer application rate and farmers' risk aversion coefficient. These results reveal not only substantial potential of investing in small-scale irrigation in Nigeria, but also financial risks in the investment and importance of linking irrigation investment decisions to agricultural policies beyond irrigation to create coordinated strategy for agricultural development.

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1. Introduction

Nigeria is the most populous country in Africa. Like many other Sub-Saharan countries, Nigeria has long been beset with poverty. According to the World Bank (2015), 46% of Nigerian people live in poverty. The prevalent poverty is also accompanied by high food insecurity. Titus and Adetokunbo (2007) found that the food insecurity incidence for the urban households is 49%. In another study, Akinyele (2009) reviewed evidence/knowledge from various sources on food and nutrition in rural Nigeria and concluded there is even more widespread food insecurity in rural areas: the malnutrition level of children is as high as 56 percent in a rural area of South West and 84.3 percent in three rural communities in the north. Addressing the challenges of poverty and food insecurity calls for boosting agricultural production in Nigeria. Agriculture is a main economic sector in Nigeria providing employment for 70% of population of the country. An increased agricultural productivity could not only improve food security, but also bring more income and enhanced well-being to Nigeria's large rural population.

Among various options for agricultural development in Nigeria, irrigation development is perceived as an important one. Currently, crop production in Nigeria is predominantly rainfed; the irrigated agriculture accounts for only 1% of cultivated area in the country (FAO AQUASTAT, 2017). This rainfed agriculture renders crop production in Nigeria vulnerable to climatic variability, both intra-annually and inter-annually. The intra-annual variability is characterized by the seasonality of rainfall. Nigeria has tropical climate with rainy and dry season(s) alternating with each other. Rainfed farming practices concentrate or are limited to months of the rainy seasons. When it comes to inter-annual variability, a large portion of agriculture in Nigeria is located in the Sudano–Sahelian region, which is historically prone to drought (Tarhule and Woo, 1997; Batterbury and Warren, 2001). As a natural phenomenon originating from inter-annual variability of precipitation, drought has huge impact on crop production and is linked to several famines in Nigeria's history (Van Apeldoorn, 1981; Olaniran, 2002). The development of irrigation may help remove these barriers imposed by climate variability on rainfed crop production and substantially benefit agricultural sector in Nigeria. Support for irrigation development has been embedded in the Agricultural Transformation Agenda (ATA) which guides current agricultural policies in Nigeria (FMARD, 2011).

This paper presents a study to assess investment potential of expanding irrigation in Nigeria. We focused on small-scale irri-

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gation. The existing irrigation systems in Nigeria consists of both small-scale and large-scale irrigation schemes. Small-scale scheme is the dominant one and accounts for more than 95% of the cropland area under irrigation in Nigeria (FAO AQUASTAT, 2017). The small irrigation schemes here refers to all irrigation developed under private ownership of smallholder farmers for harvesting water resources to augment water supply for crop production. It is in contrast to dam-based large-scale irrigation which use water in the reservoir behind the dams and are public financed. The implementation of small-scale irrigation may involve a collection of technologies, such as pulley-bucket, motor pumps and small reservoirs etc. Small-scale irrigation is viewed as a "bottom-up" or "grass-roots" approach to development (Kay, 2001), and has received much attention in recent years (Abric et al., 2011; de Fraiture and Giordano, 2014; Gebrehiwot et al., 2015). In Nigeria, the1960s and 1970s witnessed several initiatives to develop large-scale irrigation schemes, and these initiatives formed a part of Nigerian government's effort to promote production of staple crops through introducing modern agricultural inputs and technologies (Abalu and D'Silva, 1980; Okolie, 1995; Shimada, 1999). However, these large-scale irrigation projects are generally perceived inefficient and ineffective. Only 20% of area equipped with large-scale irrigation is actually irrigated (Takeshima et al., 2010). The factors that lead to the failure of large-scale irrigation project include delayed construction, poor management, difficulty in recovering capital costs and less-than-expected water supply (Adams, 1991). Thus, there was a policy shift into small-scale irrigation since 1980s. As a demonstration of the shifted policy interest, on the Agricultural Transformation Agenda, priority is given to the rehabilitation of existing irrigation projects where reservoirs already exist rather than to constructing new irrigation reservoirs (FMARD, 2011), and in the World Bank's three phases of the National Fadama Development Programme (Fadama I, II, and III), focus was made on providing financial support for farmers to acquire productive assets, such as irrigation pumps, for practicing small-scale irrigation (Nkonya et al., 2012). It is anticipated small-scale irrigation will constitutes main form of future irrigation development in Nigeria.

The rest of the paper is organized as follows: in Section 2, we describe the data and present the methods we used and developed for the study. The assessment results are reported in Section 3, and their policy implications and a few limitations of the study are further discussed in Section 4.

2. Data and methods

2.1. Small-scale irrigation expansion pathways in Nigeria

Irrigation practices by smallholder farmers in Nigeria and other Sub-Saharan African countries have been investigated in a number of studies. Characteristics of existing irrigators' behavior revealed in these studies allow us to develop a vision on the future expansion pathways of small-scale irrigation in Nigeria, which underpins our analysis.

Specifically, using data collected from Living Standard Measurement Survey (LSMS) Takeshima and Edeh (2013) analyzed the topology of existing irrigated agriculture in Nigeria. They found that in Nigeria irrigation, mainly practiced at small scale, occurs in both dry season and rainy season. The identified major crops irrigated in the dry season are vegetable, rice and maize. This result is consistent with the observations from other Sub-Saharan Africa countries (Meinzen-Dick et al., 1994; Girma and Seleshi, 2007; Namara et al., 2011): irrigation helps extend crop production into dry season; farmers tend to use irrigation to cultivate high value or critical food crops to generate additional income. LSMS data, on the other hand, also show that in rainy season, in addition to vegetables, rice and maize, farmers also irrigate coarse grains (sorghums and millets) and legumes (e.g., cowpea and groundnuts). The economics behind rainy season irrigation is less understood, but the role of irrigation in increasing the resilience of rainy season farming has been well recognized (Fox and Rockström, 2003). That is to say, investment in irrigation may offers insurance against erratic and unreliable rainfall; farmers practice irrigation in prolonged dry spells to mitigate drought conditions and to maintain yields in drought years.

In view of the findings from Takeshima and Edeh (2013) and the different roles irrigation may play in crop production in Nigeria, we assumed two groups of crops (Table 1) which could be potentially irrigated by expanded small-scale irrigation schemes. We then estimated irrigation expansion potential associated with the two groups of crops separately using different approaches. The first group consists of dry-season vegetables, dry-season maize and dry- and rainy-season rice. We also include wet-season rice into this group considering intensive water requirement in rice production. It was assumed that irrigation will determine the cultivation scale of these irrigated crops. An optimization model was formulated to estimate the scale of irrigation expansion based on long-run cost benefit of irrigated crop production, by assuming irrigation expansion would maximizes net revenue received by farmers. The second group of crops include rainy season maize, vegetables, sorghum, millet, cowpea, groundnuts and other main crops cultivated in rainy season (sweet potato, yam and cassava). Given the supplemental nature of irrigation in rainy season crop production, it is important to account for variability of crop production induced by variable climate and farmers' attitudes towards risks. It has shown that farmers are generally risk averse, and the risk aversion attitude is a factor influencing their decisions in agricultural technology adoption (Binswanger, 1980; Yesuf and Bluffstone, 2009; Brick et al., 2012; Nielsen et al., 2013). Risk analysis techniques were thus applied to estimate adoption rates of supplemental irrigation associated with crops in the second group.

2.2. SPAM, ex-ante irrigation map and SWAT

The main data sets we used in the study are listed in Table 2. Two major ones are the SPAM database and an ex-ante Nigerian irrigation site map developed by Taiwo et al. (2010). SPAM is an acronym for Spatial Production Allocation Model (You et al., 2014a). It is designed to downscale national and sub-national agricultural statistics for crop production to a 5 arc-minute (approximately 10 km × 10 km on equator) grid. SPAM database with global coverage has been created and is available at http://mapspam.info. In this study, an updated national SPAM database for Nigeria was developed. The SPAM-Nigeria estimates spatial distributions of cultivation area and yields of main crops in Nigeria circa 2006 (calculated as averages between 2005 and 2007 and a distinction between rainfed and irrigation system is made) and provides a baseline for our analysis (see Appendix I for more details on SPAM methodology and data in SPAM-Nigeria database).

Another data set, Taiwo et al.'s (2010) irrigation map shows the possible sites for the uptake of small-scale irrigation in Nigeria (Fig. 1). The input data used in creating this map include topography, climate, soil and a mosaic of high-resolution LULC (land use and land cover) remote sensing images (Landsat and Spot). Field survey work was also conducted to collect environmental attribute information on existing irrigation farms. Supervised learning algorithm was used to train a classifier to identify land with irrigation development suitability. The total area of these sites on this map amounts to 14 million hectares. A limitation of this mapping product is that no explicit consideration is given to such factors as water balance and economic viability, which may serve as key constraints for irrigation development. In our study, Taiwo et al.'s (2010) irrigation map was used as an ex-ante estimate of the upper bound

Table 1
Small-scale irrigation expansion pathways in Nigeria.

	Group I	Group II
Main candidate crops under irrigation	Dry season vegetables, rainy and dry season rice, rainy season maize	Maize, sorghum, millet, groundnuts, yam, cowpea, sweet potato, cassava and vegetables in rainy season
Goals/roles of irrigation investment	Income generation; act as driving force for dry season crop production expansion	Supplemental; contribute to improving climate resilience of crop production

Table 2
Main data sets used in small-scale irrigation expansion potential assessment in Nigeria.

Data set	Source
Cropping area and crop yields	Spatial Production Allocation Model (SPAM) (You et al., 2014a)
Ex-ante estimate of spatial extent with small-scale irrigation potential	Taiwo et al. (2010)
Elevation	USGS HydroSHEDS (http://hydrosheds.cr.usgs.gov/index.php)
Climate (precipitation, temperature and solar radiation)	Global Weather Data for SWAT (http://globalweather.tamu.edu), derived from the National Centers for Environmental Prediction (NCEP) Climate Forecast System Reanalysis (CFSR)
Soil	FAO/UNESCO Soil Map of the World and derived soil properties (http://www.waterbase.org/resources.html)
Land cover	Global Land Cover (GLC) 2000, developed by European Commission Joint Research Centre (http://forobs.jrc.ec.europa.eu/products/glc2000/data_access.php)

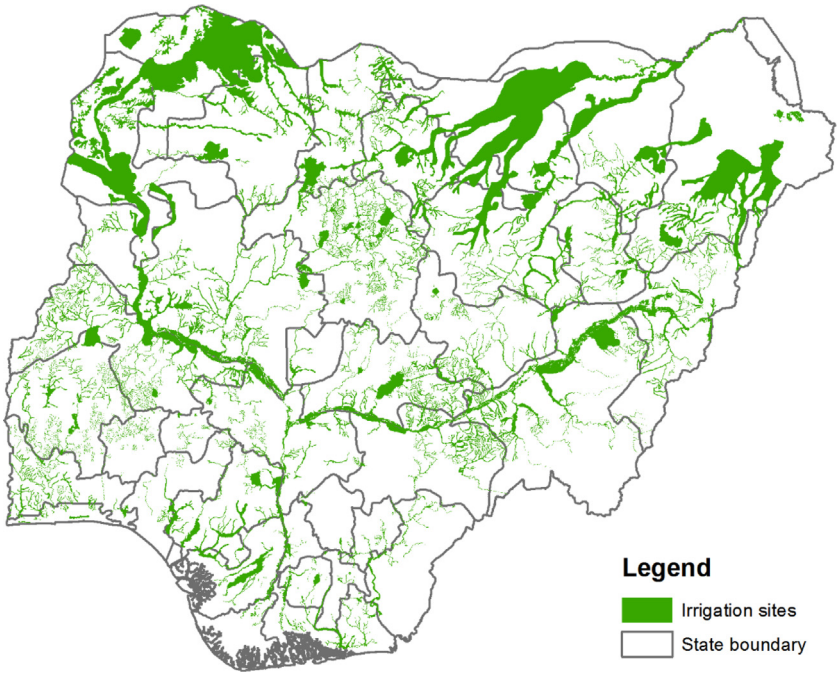


Fig. 1. Ex-ante estimates of areas with smallholder irrigation potentials in Nigeria (Taiwo et al., 2010).

of spatial extent of land area in which irrigation expansion could occur in both dry and rainy seasons.

Our modelling also needs to estimate the amount of water resources available for irrigation, irrigation water demand and effects of irrigation on crop productivity (see Sections 2.3 and 2.4) through hydrologic modeling and crop simulation exercises. The modeling tool we used here is the Soil and Water Assessment Tool (SWAT) (Arnold et al., 1998). SWAT is a comprehensive hydrologic and agricultural model. Its capacity in large-scale hydrologic simulation in African countries has been validated in a number of studies (Schuol et al., 2008; Easton et al., 2010; Xie et al., 2012). On crop simulation side, the simulation algorithm in SWAT originates from the EPIC (Erosion Productivity Impact Calculator) model (Williams et al., 1984), and is capable of simulating the physiological development of crop plants and calculating their yields under various environmental stresses (water, temperature, nutrients etc.). Functions to simulate irrigation activities are also provided. A detailed description on functionality and simulation algorithm of the SWAT model can be found in Neitsch et al. (2005). The elevation, climate, soil and land cover data listed in Table 2 were used to support the setup of the SWAT model in this study, and two versions of the SWAT model were created: in dry season analysis, a sub-watershed discretization scheme was applied in model development while in rainy season analysis, we re-parameterized the SWAT model to perform the crop simulation at SPAM pixel level.

2.3. Method for assessing irrigation expansion potential in dry season

The optimization model we used to determine the scale of dry-season irrigation is described below. For modeling purpose, we partitioned Nigeria into 289 river basins (Fig. 2a) and 122 regional markets (Fig. 2b), and defined food production units (FPU) as intersected areas between river basins and regional markets (Fig. 2c). A

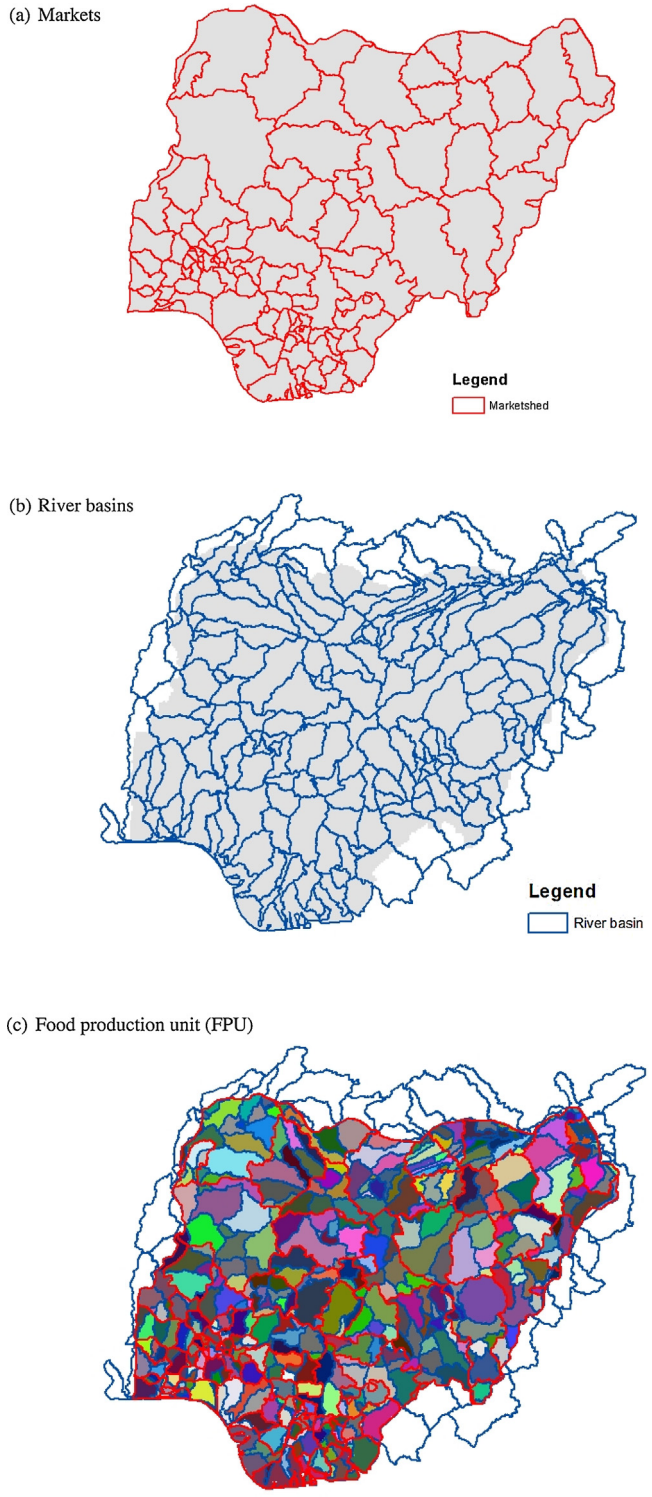


Fig. 2. Marketsheds, river basins and food production units (FPUs) in Nigeria. The marketshed delineation is according to proximity (measured by travel time) to market centers or settlements with a population >50,000. Source of data: Zhe Guo, Harvest Choice, 2013.

total of 614 FPUs were defined in our model, and small-scale irrigation expansion areas by FPU, A_{fc}, act as decision variables in the analysis, where subscript f denotes FPU (f = 1, 2, 3···, 614) and subscript c denotes crop (c = 1, 2, 3 *and* 1 *for rice*, 2 *for maize and* 3 *for vegetables*).

In deciding A_{fc}, we assumed farmers to maximize their total profit ($\Delta NetR$) by comparing the crop revenue before and after the irrigation expansion. The objective function of this optimization problem can be written as

$$\max \Delta NetR = \sum_{m}\sum_{c}\left[Prod_{mc}\cdot Pr_{mc}\cdot PM_c - \sum_{f\in m}A_{fc}\cdot IC - \sum_{f\in m}LC_{fc} - Prod_{mc,init}\cdot Pr_{mc,init}\cdot PM_c\right] \quad (1)$$

where subscript m denotes delineated market (m = 1, 2, 3···, 122), $Prod_{mc}$ is the production of crop c in market m after irrigation expansion (ton/year), Pr_{mc} is the price of crop c in market m after irrigation expansion ($/ton), $Prod_{mc,init}$ is the production of crop c in market m prior to irrigation expansion (ton/year), $Pr_{mc,init}$ is the price of crop c in market m prior to irrigation expansion ($/ton), PM_c is the profit margin of producing crop c (0–1, excluding irrigation costs), IC is annual costs of irrigation per unit of irrigated area ($/ha-yr), and LC_{fc} are terms defined to represent additional costs associated with expanding irrigated rice production ($/yr) (see explanation below).

In objective function (1), $Prod_{mc,init}$, $Pr_{mc,init}$, PM_c and IC are constants (the initial production of rice, maize and vegetables in each marketshed were derived from the SPAM database and see Tables 3 and 4 for values of initial price, profit margin and irrigation costs used in this analysis), A_{fc} while $Prod_{mc}$, Pr_{mc} and LC_{fc} are functions of $A_{fc.}$ The rationale of modeling $Prod_{mc}$ and Pr_{mc} as functions of A_{fc} is that we expect that as irrigation tend to increase the production and supply of crop products on markets, prices of these commodities would drop. Such price crop would in turn affect the economic profitability of crop production and thus finally constrain the expansion of irrigation. In this study, we chose to use the Dynamic Research EvaluAtion for Management (DREAM) model (Wood et al., 2005) to evaluate the variation of $Prod_{mc}$ and Pr_{mc} under various irrigation schemes. DREAM is a partial equilibrium model designed to evaluate economic returns and market consequences of the adoption of production-enhancing technologies in one or more innovating regions. The DREAM model used in this study assumes the same multiple domestic market delineation scheme as demonstrated in Fig. 2(a) in the modeling for rice, maize and vegetables, but markets for three crops are cleared at different levels. Nigeria is the second largest rice importing country in the world. In our model, rice market is cleared internationally (with an additional Rest-of-World, or ROW, market is defined). In terms of maize, according to official data (FAOSTAT, 2016), there are only small quantities of maize being exported and imported. This is largely a result of Nigeria's foreign trade policy. Nigerian government placed maize on the export prohibition list to ensure domestic maize supply. However, it is shown that unofficial trade exists between Nigeria and neighboring countries (Cadoni and Angelucci, 2013). In this study, we assumed a regional market across West Africa countries. As for vegetables, the recorded quantities of vegetable import and export are small relative to total domestic production and consumption. The vegetables trade with foreign countries are ignored, and the supply and demand of vegetables are cleared at national level.

During the analysis, it is necessary to specify the expected yields of crops under irrigation in FPUs as input. There is no sufficient data from SPAM to empirically estimate such yields for all FPUs across the nation. To circumvent this problem, we applied multiplying factors to FPU-wide average rainfed yields derived from SPAM data and took the amplified rainfed yields as estimates for irrigated yields. This approach helps preserve the observed spatial variability of productivity in crop production, which may be related

to non-simulatable input-output market conditions and other management factors. In this study, the specified irrigated yields of rice and maize range between 4~6 ton.ha and 4~5 ton/ha in high-yielding FPUS, which are close to their estimated attainable yields in Nigeria (Nwafor, 2009; Nkonya et al., 2010); the yield improvement induced by irrigation in vegetable production is assumed to be 30%.

The optimization is subjected to the following constrains:

$$A_{fc} \geq 0, \quad \forall f, c \tag{2}$$

$$\sum_{c} A_{fc} < A_{f,max}, \quad \forall f \tag{3}$$

$$\sum_{f \in r} \sum_{c} (w_{fc} \cdot A_{fc}) < Q_r, \quad \forall r, \tag{4}$$

where r is the subscript for river basin, w_{fc} is the intensity of consumptive use of irrigation water in food production unit f and for crop c (m^3/ha-yr), Q_r is the maximum amount of water available for irrigation in river basin r (m^3/yr), and $A_{f,max}$ is the maximum possible area for irrigation expansion in food production unit f (ha).

The first sets of constraints in Eq. (2) are non-negative constraints, and the second set of constraints state the maximum irrigation expansion areas in each FPU. As mentioned, Taiwo et al. (2010) provides an ex-ante estimate of land are with irrigation expansion possibility. Considering that in Nigeria it is difficult for farmers to acquire new land for farming due to high population density and insecure land tenure, we further assumed that the irrigation expansion is limited to existing cropland. So $A_{f,max}$ in Eq. (3) refers to existing cropland area which falls into in the extent of land with irrigation expansion possibility shown on Taiwo et al.'s irrigation suitability map, and its value was derived through an overlay analysis integrating Taiwo et al.'s irrigation suitability data and cropland area distribution data from SPAM. Moreover, in the analysis, we assumed that rice cultivation is always in a double-cropping mode and that farmers always first convert rainfed rice fields to irrigated land before more land is brought to rice production. LC_{fc} in the objective function (1) is included to reflect the opportunity costs resulting from substituting rice for other crops in rainy season on expanded rice land and is calculated

$$LC_{fc} = \begin{cases} \left(A_{fc} - A^*_{f,rice}\right) \cdot C & c = 1 and A_{fc} > A^*_{f,rice} \\ 0 & otherwise \end{cases} \tag{5}$$

where $A^*_{f,rice}$ is the existing cultivation area of rainfed rice within the extent of $A_{f,max}$ in FPU f, and C is the cost per unit area incurred by substituting rice for other crops and was assumed to be a constant of USD 500/ha-yr in this study.

The third set of constraints is about water availability. We included rainy season rice in this component of analysis. However, results from pilot water balance analysis suggests that water scarcity does not constitute a constraint for irrigated rice production in rainy season. Therefore, the intensity of consumptive use of irrigation for rice in Eq. (4) actually denotes the irrigation water consumption in dry season only, and similarly Q_r denotes the amount of available water resources in dry season as well. LSMS data show rice and maize and vegetables in dry season mainly irrigated using water from streams and rivers. Q_r is thus estimated as 70% of runoff in basin r produced in dry season months using the version of the SWAT model with sub-basin delineation scheme and under the assumption that 30% runoff is preserved for other types of users and for environmental purpose. This version of SWAT model was calibrated and validated using monthly stream flow data from the Niger Basin Authority (NBA, http://www.abn.ne/index.php?lang=en) Global Runoff Data Centre (GRDC, http://www.bafg.de/GRDC/EN/Home/homepage_node.html) and Japan International Cooperation Agency (JICA, 1995) (see Appendix II for more details about SWAT hydrologic calibration). The irrigation water consumption intensity was estimated using grid-based SWAT model by differencing calculated evapotranspiration of cropland in rainfed and irrigated cases and with assumed irrigation efficiency factor values of 0.6 for rice and 0.8 for maize and vegetables. The grid-based estimates for irrigation water consumption intensity were aggregated to FPU level and are used in Eq. (4).

2.4. Method for assessing irrigation potential in rainy season

Given the supplemental nature of irrigation in rainy season production, we assumed that there is no change in crop mix caused by irrigation investment. For each crop in group II, the first step of the analysis is to use crop simulation module of the SWAT model to reconstruct the rainfed yields from 1981 to 2010 at SPAM pixel level and to calculate profits of producing these crops:

$$r^{rf}_{icj} = P_c \cdot y^{rf}_{icj} \cdot pm_c \tag{6}$$

where r^{rf}_{icj} is the profit per unit area of producing crop c ($c = 1, 2, \cdots, 9$) in year i ($i = 1, 2, \cdots, 30$) and pixel j (\$/yr-ha), P_c is the price of crop (\$/ton), y^{rf}_{ij} is the estimated rainfed yield of crop c in year i and pixel j, and pm_c is the profit margin for the production of crop c.

We also used the SWAT model to estimate the time series of irrigated yields of the nine crops $y^{ir'}_{icj}$(\$/yr-ha); in the simulation the irrigation infrastructure was assumed in operation every year. The "actual" crop yields which can be achieved after the irrigation investment are

$$y^{ir}_{icj} = \begin{cases} y^{ir'}_{icj} & \text{if } P_c \cdot \left(y^{ir'}_{icj} - y^{rf}_{icj}\right) \cdot \text{pm}_c - C_{op} > 0 \\ y^{rf}_{icj} & otherwise \end{cases} \tag{7}$$

where y^{ir}_{icj} is the achieved yield after the irrigation investment (\$/ton), and C_{op} is the operating costs of irrigation (\$/ha-yr). Irrigation is not necessarily practiced every year and only occur if the revenue increment exceeds the operating costs of irrigation.

The corresponding profits of crop production after irrigation investment is calculated as

$$r^{ir}_{icj} = P_c \cdot y^{ir}_{icj} \cdot pm_c - C_{cap} - I(icj) \cdot C_{op} \tag{8}$$

where r^{ir}_{icj} is the profit per unit area of producing crop c in year i and pixel j (\$/yr-ha), C_{cap} is the amortized capital costs in irrigation development (\$/ha-yr), and $I(\cdot)$ is an indicator function: $I(icj) = 1$ if in year i irrigation occurs and $I(icj) = 0$ otherwise.

The irrigation investment decision is based on comparing certainty equivalents of economic return of crop production per unit area prior to and after irrigation investment. The certainty equivalent of economic return of crop production is the amount of economic return which provides farmers with the same amount of utility as what they expect to receive from crop production in an uncertain environment when faced with yield variability induced by variable climate. Using certainty equivalent as decision criterion in rainy season analysis allows for incorporating farmers' risk aversion attitude into the analysis (Gollin, 2006).

In this study, the farmers' utility is modeled using negative exponential utility function

$$U(r) = 1 - \exp(-\gamma r) \tag{9}$$

where U is farmer's utility; r is the profit of crop production per unit area (\$/yr-ha); γ is risk aversion coefficient (yr-ha/\$), a constant characterizing decision maker's risk attitude. For risk averse decision makers (e.g. farmers in this study), γ has a positive value (>0), which leads to a concave utility function or implies the marginal

Table 3
Crops prices and profit margins.

Crop	Price ($/ton)[1]	Profit margin	Crop	Price ($/ton)[1]	Profit margin
Rice	367–440	0.6	Vegetables	800	0.8
Maize	257–396	0.5	Sorghum	367–440	0.4
Millet	367–440	0.4	Sweet potato	250	0.3
Yam	220–293	0.2	Groundnut	330–403	0.4
Cowpea	587–880	0.4	Cassava	160	0.2

Note: Prices of rice, maize, sorghum, millet, yam and groundnuts and cowpea by political region are used in this study and derived from Living Standard Measurement Survey. Other prices are obtained from FAO PriceStat at national level.

utility provided by one monetary unit of income increment is diminishing. The larger the value of γ is, the higher of the degree of decision maker's risk aversion, or the more weights farmers put to producing crop in drought years to meet their basic needs.

The expected utility of producing a given crop per unit area is calculated using the empirical distribution of the crop yields estimated through crop simulation

$$EU_{cj}^{rf} = \frac{1}{n}\sum_{i=1}^{n}\left[1 - \exp\left(-\gamma \cdot r_{icj}^{rf}\right)\right] \quad (10)$$

or

$$EU_{cj}^{ir} = \frac{1}{n}\sum_{i=1}^{n}\left[1 - \exp\left(-\gamma \cdot r_{icj}^{ir}\right)\right] \quad (11)$$

where EU_{cj}^{rf} and EU_{cj}^{ir} are the expected utilities from producing crop c in SPAM pixel j prior to and after irrigation investment, respectively. n is he number of years in SWAT crop simulation ($n = 30$).

The certainty equivalents of economic return of crop production are calculated as

$$CE_{cj}^{rf} = \frac{\ln\left(1 - EU_{cj}^{rf}\right)}{-\gamma} \quad (12)$$

or

$$CE_{cj}^{ir} = \frac{\ln\left(1 - EU_{cj}^{ir}\right)}{-\gamma} \quad (13)$$

where CE_{cj}^{rf} and CE_{cj}^{ir} are the certainties of economic returns of crop production in rainfed case and in the case with irrigation infrastructure ($/ha-yr).

Irrigation investment is recommended in SPAM pixel j if

$$CE_{cj}^{ir} > CE_{cj}^{rf} \quad (14)$$

Taiwo et al.'s (2010) ex-ante irrigation map has a resolution of 50 m, while the pixel size in SPAM is approximately 10 km by 10 km. In view of the difference in spatial resolution between SPAM data and ex-ante irrigation map, the area with irrigation investment potential in a SPAM pixel for a crop is estimated as

$$A_{cj}^{ir} = \frac{A_{SPAM,c,j}^{rf}}{A_{SPAM,j}^{total}} \cdot A_{ex-ante,j} \quad (15)$$

where A_j^{ir} is the estimated rainfed area of crop c in pixel j potentially convertible for irrigation (ha), $A_{SPAM,j}^{total}$ is the total land area in the SPAM pixel, $A_{SPAM,c,j}^{rf}$ is the SPAM estimate for rainfed cultivation area of crop c in rainy season, and $A_{ex-ante,j}$ is the ex-ante estimate for land area with irrigation investment potential derived from Taiwo et al.'s irrigation map (ha).

Note that demand for rainy season irrigation occurs in drought years in which surface water resources tend to become scarce. However, groundwater may serve as a source of water for irrigation during drought periods. In fact, LSMS data show that a large portion of existing irrigation activities in rainy season are supplied by groundwater (Takeshima and Edeh, 2013). There is currently a lack of data to support a national assessment on groundwater exploitation potential for irrigation in Nigeria. In this study, we chose to apply no constraint of water availability in the rainy season analysis, and this may constitute a main source of uncertainty in the analysis. For the same reason of data scarcity, we also ignored inter-annual variability in crop price and irrigation operating costs. Constant price and irrigation operating cost values were used in the analysis.

Table 4
Irrigation costs under baseline conditions ($/ha-yr).

(a) Rice, dry-season maize and vegetables

Crops	Irrigation costs ($/ha-yr)
Rice (two seasons: dry + rainy)	1500
Maize and vegetables	500

(b) Rainy season

Component	Costs ($/ha-yr)
Capital costs	60
Operating costs	125

2.5. Parameters for cost-benefit calculation and sensitivity analysis

A set of values of crop prices, profit margins and irrigation costs we used in this study are shown in Tables 3 and 4. The irrigation costs vary by technology. In the analysis, we assumed that motor pump is a representative technology used for irrigating rice and dry-season maize and vegetables and rainy season irrigation mainly involves use of low-cost water lifting technologies (such as pulley-bucket). Taiwo et al.'s survey (2010) showed that there is lack of mechanization in current small-scale irrigation practice, but farmers who practice dry-season irrigation for income generation are often in a better economic position and are more likely to adopt mechanized irrigation. The cost figures in Table 4 were specified to reflect the cost levels of two type of irrigation technologies. A higher cost figure was also specified for rice irrigation than for irrigation of dry-season maize and vegetables since more intensive irrigation operation is required to maintain the flooded state of rice paddy. Furthermore, according to methods described in Sections 2.3 and 2.4, it is necessary to distinguish between operating component and capital component of irrigation costs in rainy season analysis, and the specified irrigation costs for the two components are listed separately (Table 4b).

Past irrigation investment analyses on Sub-Saharan countries (You et al., 2011; Xie et al., 2014 and You et al., 2014b) reveal that the analysis results are sensitive to input parameters, especially those related to calculating cost-benefit of irrigation expansion. In rainy season analysis, risk aversion coefficient (γ) is also a key parameter in certainty equivalent calculation. There is no study to estimate the farmers' risk aversion coefficient empirically in Nigeria (Patrick

Table 5
Estimated irrigation expansion potential for rice, dry-season maize and vegetables.

(a) Baseline		
	Area (×1000 ha)	Net revenue (×10^6 USD/yr)
Rice	421	189
Maize	122	9
Vegetables	458	427
Total	1001	625
(b) Reduced irrigation costs		
	Area (×1000 ha)	Net revenue (×10^6 USD/yr)
Rice	1031	736
Maize	415	66
Vegetables	535	551
Total	1981	1353
(c) Reduced irrigation efficiency		
	Area (× 1000 ha)	Net revenue (× 10^6 USD/yr)
Rice	399	180
Maize	120	8
Vegetables	456	422
Total	975	610

Ward, personal communication, 2013). A value of 0.03 is assumed in the analysis under baseline conditions (Ngwira et al., 2013). Considering the uncertainty and output sensitivity associated with these input parameters, sensitivity analysis was conducted on irrigation costs (perturbing values of crop prices and profit margins will provide similar insight) and, in the rainy analysis, on the risk aversion coefficient to understand how the estimated areas with small-scale irrigation potential could be affected by input uncertainty of these parameters. The irrigation sensitivity analysis will also help provide a sense of how sensitive the estimated irrigation development potential is to the choice of irrigation technology.

2.6. Sensitivity analysis on irrigation efficiency and fertilizer application rates

In addition to irrigation costs, uncertainty may also originate from other sources. While it is not possible to provide exhaustive analysis on uncertainty from all sources, additional sensitivity analysis on the following factors were carried out:

2.6.1. Irrigation efficiency

Irrigation efficiency is an important parameter of the dry-season assessment model (Section 2.3). the documented values of irrigation efficiency in African region range between 0.4 and 0.8 (FAO, 1997). There is large uncertainty associated with these estimates. The irrigation efficiency figures we specified in Section 2.3 are in the optimistic range. In sensitivity analysis on irrigation efficiency, the value of this parameter was reduced from 0.6 to 0.4 for rice and 0.8 to 0.6 for dry-season maize and vegetables.

2.6.2. Synergy between water and nutrient management

In rainy season analysis, additional sensitivity analysis was also carried out to investigate synergy between irrigation and other agricultural production technologies. Agricultural productivity is influenced by many input factors other than water. Rainfed crop production in Nigeria is mostly in the low input, subsistence mode. We speculated that the low input levels in crop production may restrict the efficacy of irrigation by imposing constraints on crop yield and making crop yield less responsive to water application from irrigation. In this sensitivity analysis, we tested the hypothesis by focusing on exploring the linkage between water and fertilizer inputs. Fertilizer use in Nigeria is far lower than FAO recommendations and the levels in other developing countries in South Asia and Southeast Asia. The low use of fertilizer has been identified as one of main reasons for current low productivity of crop production in Nigeria (Liverpool-Tasie et al., 2010). In the sensitivity analysis, we increased the nitrogen fertilizer application rates in SWAT crop simulation and re-estimate small-scale irrigation potential in rainy season using the rainfed and post-investment yield estimates simulated at the improved fertilizer use level.

3. Results

The areas in Nigeria with small-scale irrigation expansion potential, estimated with price and cost figures in Tables 3 and 4, are shown Tables 5 (a) and 6 . In discussions below, they are referred as estimates under baseline conditions.

Under the baseline conditions the small-scale irrigation development potential associated with production of rice, dry-season vegetables and dry-season maize is about 1 million hectares in Nigeria. Most of the potential comes from vegetable and rice. The recommended irrigation development area is 0.46 million hectares for dry-season vegetable cultivation and 0.42 million hectares for rice production. Investing in small-scale irrigation to produce these two crops will bring US$427 million and US$189 million of additional income to their growers per year. Less potential is found for dry-season maize: the estimated potential area is 0.12 million hectares and the profit increment from the irrigation expansion is US$9 million/year. Maps displaying densities of irrigation potential area by FPU, calculated by dividing estimated potentially irrigable areas for individual crop (and the sum of all the crops for the composite map) by the total area of FPU, are shown in Fig. 3. Compared to the irrigation potential area for vegetables, the irrigation potential of rice mostly concentrates in the central or south central parts of Nigeria. The irrigation potential for dry-season maize is located in a few states in the central north.

The baseline estimate for small-scale irrigation expansion potential derived in rainy season analysis is 0.56 million hectares. It consists of 129, 000 ha for maize, 78,000 ha for sorghum, 186,000 ha for millet, 9000 ha for yam, 46,000 ha for cowpea, 25,000 ha for cassava and 179,000 ha for vegetables. No irrigation potential is found for sweet potato and yam. Fig. 4 shows the distribution of these potentials. As evident from the composite map, the climate variability induced irrigation investment need mainly exists in northern

Table 6
Estimated irrigation expansion potential in rainy season analysis under baseline conditions.

Crop	Irrigation potential (× 1000 ha)	Crop	Irrigation potential (× 1000 ha)
Maize	129	Sorghum	78
Millet	186	Sweet potatoes	0
Yam	9	Groundnuts	0
Cowpea	46	Cassava	25
Vegetables	179	Total	652

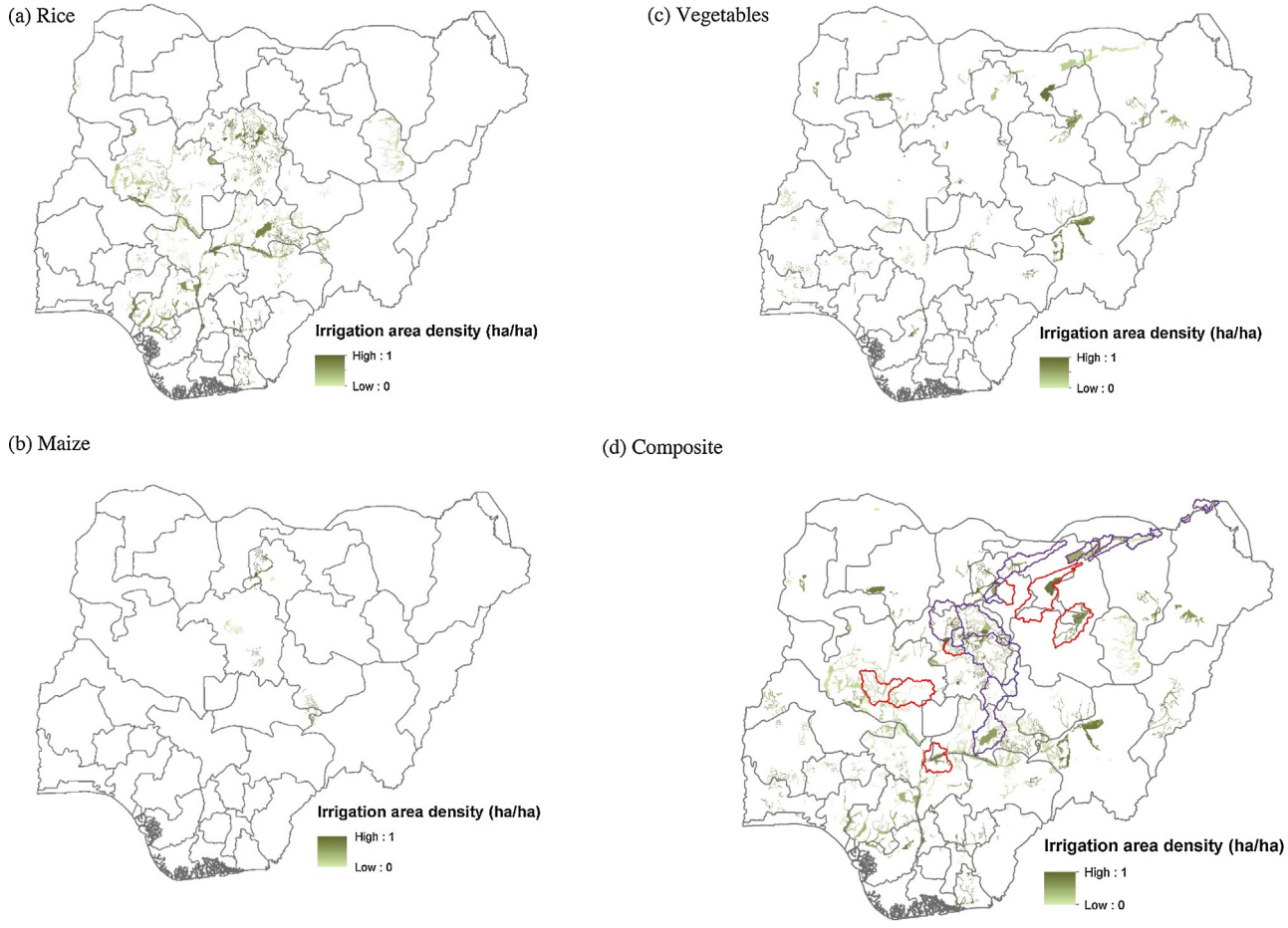


Fig. 3. Irrigation potential for rice, dry-season maize and vegetables under base conditions (subbasins bounded by purple lines are subbasins with binding water resources constraints under baseline scenario; subbasins bounded by red lines are expanded area with binding water resources constraints under "reduced irrigation efficiency" scenario). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

Nigeria. This pattern reflects spatial variation of rainfall within the country. Annual rainfall in Nigeria decreases from south to north, resulting a transition of climate type from tropical monsoon climate on southern coast to semi-arid and desert climate in regions close to Nigeria's northern border. In-depth rainfall analysis reveals that the longitudinal variation of rainfall is also associated with a later onset and earlier cessation of rainy season and higher probability of drought occurrence in the north (Adefisan and Abatan, 2015)

The results of sensitivity analysis on irrigation costs are shown in Table 5(b), Fig. 5(a) and (b). In sensitivity analysis for dry season, we reduced the irrigation cost values by 50%. As a response to the reduction in irrigation costs, the total irrigated cultivation area of three crops projected by our dry-season model is almost doubled (Table 5(b)). The irrigation potential area for rice increases to 1 million hectares, for dry-season maize rises to 0.42 million hectares and for dry-season vegetables reach 0.54 million hectares. In the sensitivity analysis for rainy season, we changed values of the capital and the operating costs of irrigation separately, one at a time. Values of the two parameters are allowed to vary between US$30 ~ 90/ha-yr (for capital costs) and between US$60 ~ 200/ha-yr (for operating costs), respectively. Curves indicating the total irrigation potential area associated with 9 rainy season crops and estimated with different irrigation cost values are plotted in Fig. 5(a) and (b). Irrigation potential area increases to 2.4 million hectares and 2.8 million hectares respectively when the capital costs and operating costs are at the low end of their value ranges and both drops to around 0.3 million hectares when the two cost parameters have a value of US$90/ha-yr or US$200/ha-yr. In both cases, as the values of two cost parameters approach to high end of their value ranges irrigation potential mainly originates from the cultivation of vegetables, which has relatively high price and profit.

The sensitivity analysis on risk aversion coefficient was conducted in a similar way (Fig. 5c). The specified uncertainty range of risk aversion coefficient is between 0 and 0.05. When the value of the risk aversion coefficient is set to 0, farmers are risk neutral and the estimated total irrigation potential area drops to 0.16 million hectares. Once again, vegetables constitutes majority of the

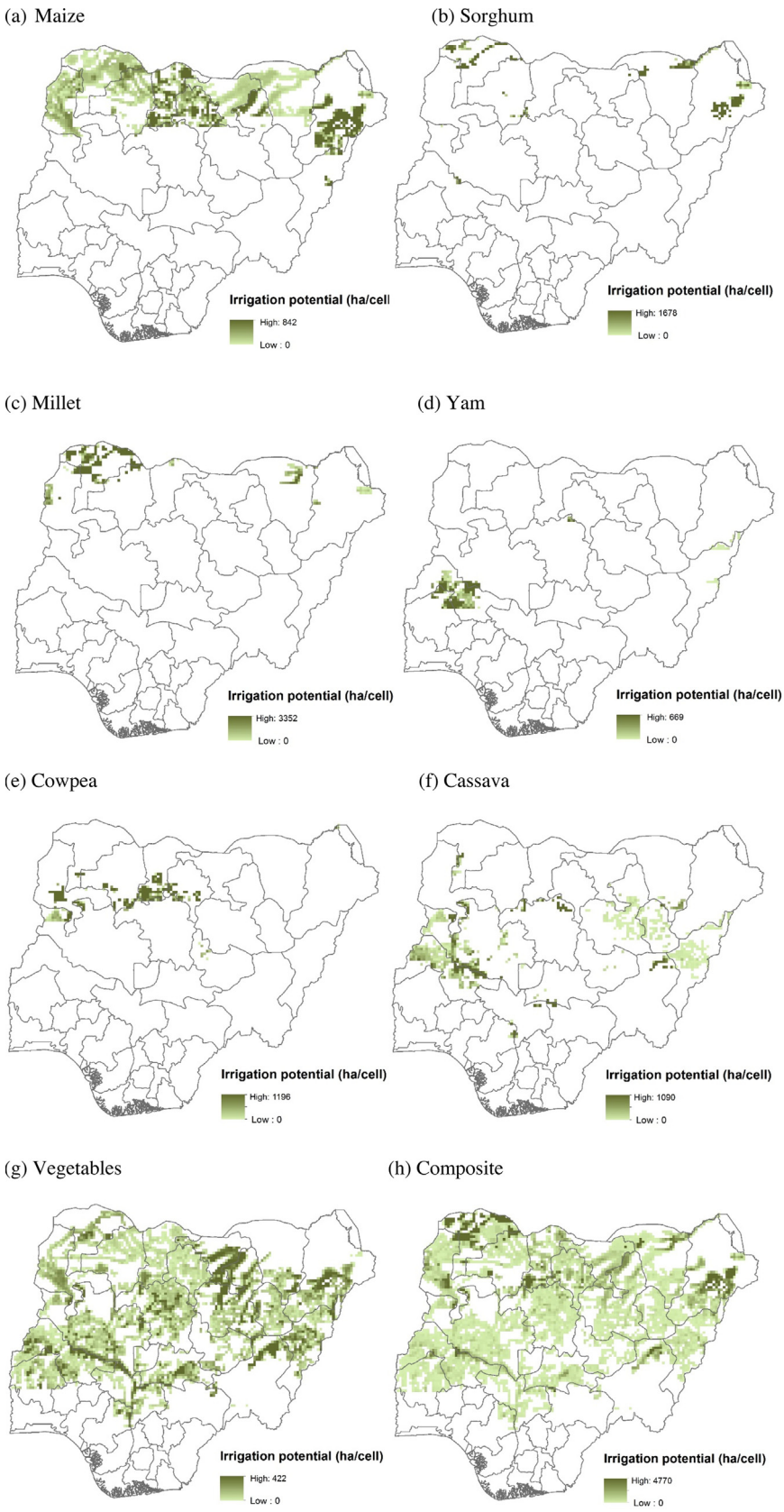
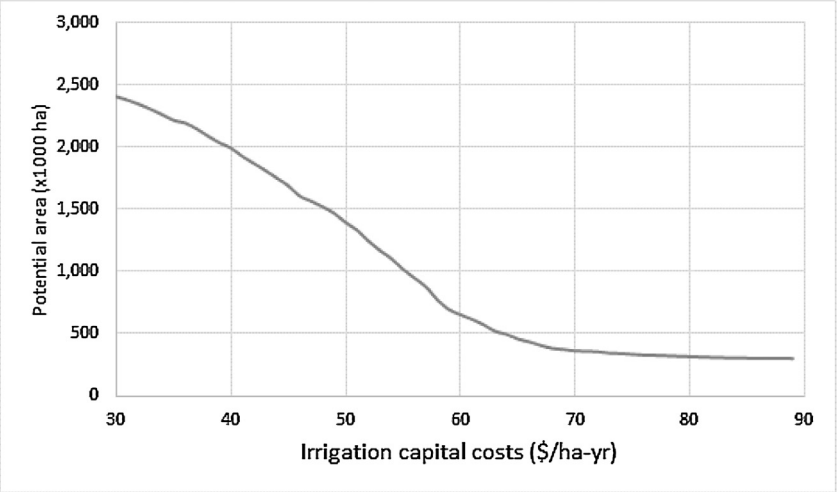


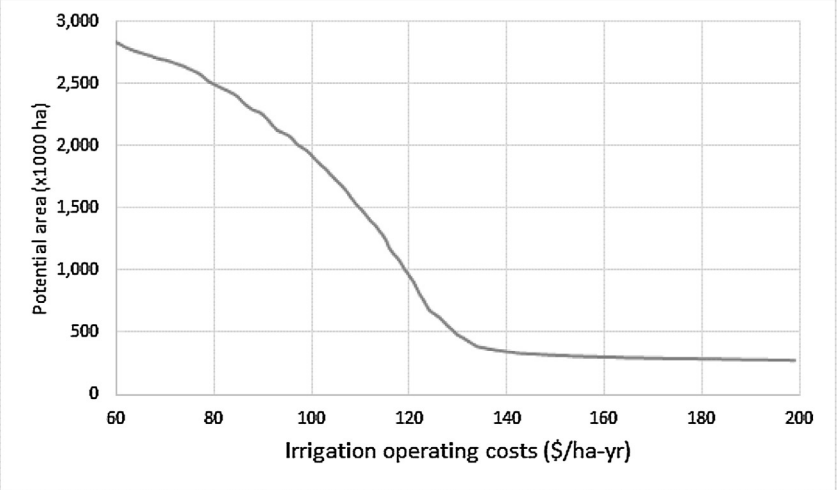
Fig. 4. Estimated irrigation potential in rainy season analysis under baseline conditions of irrigation costs and with baseline application rates of nitrogen fertilizers.

potential due to the high profitability of the vegetable production. Higher values of risk aversion coefficient, or elevated degree of risk aversion, leads to larger estimates for irrigation potential in rainy season. As the value of risk aversion coefficient increases to 0.05, the estimated total irrigation potential area rises to 1.2 million.

(a) Potential area vs. irrigation capital costs



(b) Potential area vs. irrigation operating costs



(c) Potential area vs. risk aversion coefficient

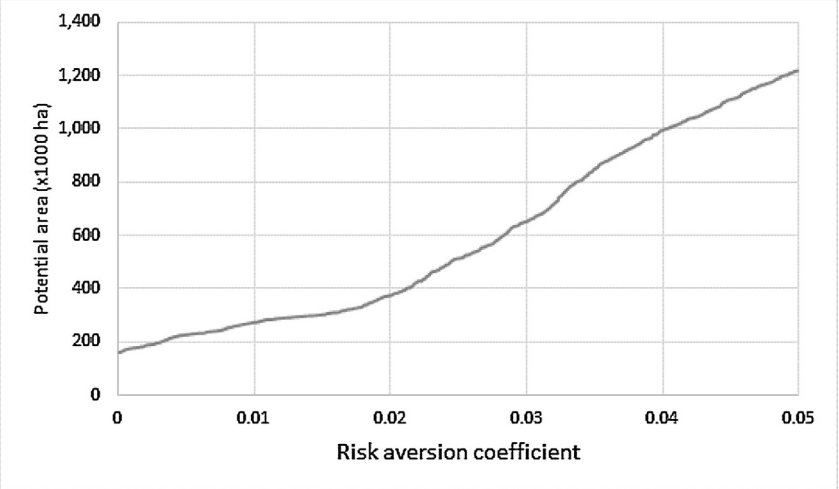


Fig. 5. Sensitivity of estimated area with small-scale irrigation expansion potential in Nigeria to irrigation costs and risk aversion coefficient in rainy season analysis.

Table 5(c) contains results of sensitivity analysis on irrigation efficiency. An expansion of area with binding water resources constraints in the model are observed when irrigation efficiency decreases (Fig. 3d). Correspondingly, the estimated irrigation potential area drops to 0.98 million hectares.

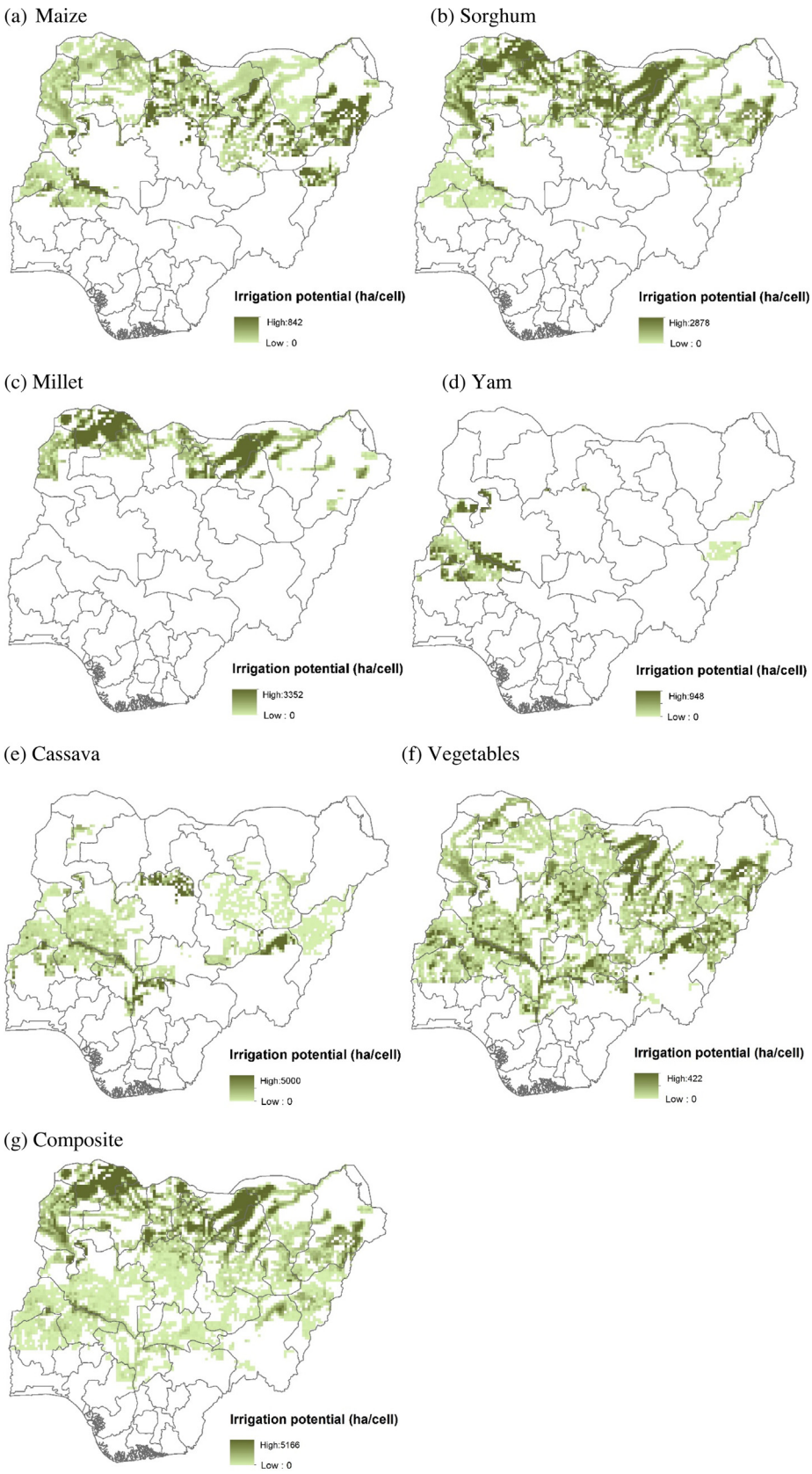


Fig. 6. Estimated irrigation potential in rainy season with enhanced nitrogen fertilizer application rates (no changes in estimated irrigation potential area for groundnuts and cowpea).

Table 7
Nitrogen fertilizer application rates used in crop simulation and simulated national average yields in rainy season analysis.

	Baseline conditions		Sensitivity analysis	
	Nitrogen application rate (kg/ha-yr)[1]	Simulated yield (ton/ha)	Nitrogen application rate (kg/ha-yr)	Simulated yield (ton/ha)
Maize	23	1.9	50	3.4
Sorghum	28	1.3	50	2.1
Millet	31	1.4	50	1.9
Sweet potatoes	18	3.3	50	4.2
Yam	9	13	20	16
Groundnuts[2]	0	1.4	20	1.4
Cowpea[2]	0	0.9	20	0.9
Cassava	3	13	20	15
Vegetables	30	5.0	50	7.0

Source: Author's estimates and FAO Fertistat.
Note: SWAT simulates nitrogen fixation effect of legumes. No significant yield improvement is projected for groundnuts and cowpea.

Table 8
Estimated irrigation expansion potential in rainy season analysis under increased nitrogen fertilizer application rates.

Crop	Irrigation potential (×1000 ha)	Crop	Irrigation potential (×1000 ha)
Maize	221	Sorghum	1148
Millet	717	Sweet potatoes	0
Yam	26	Groundnuts	0
Cowpea	46	Cassava	96
Vegetables	186	Total	2441

The nitrogen fertilizer application rates we used in various scenarios are shown in Table 7. Table 8 shows the estimated irrigation potential areas under the alternative nutriment management scenario. The results confirm our speculation that improved nutrient management tends to result in higher demand for irrigation development. As a result of the assumed enhancement in nitrogen fertilizer use, increases in irrigation potential are projected for maize (from 129,000 ha to 221,000 ha), sorghum (from 78,000 ha to 1.1 million hectares), millet (from 186,000 ha to 717,000 ha), yam (from 9,000 ha to 26,000 ha), cassava (from 25,000 ha to 96,000 ha) and vegetables (from 179,000 ha to 186,000 ha). The irrigation potential areas of these crops are shown in Fig. 6(a)–(f). The aggregated potential area for irrigation development rises from 0.65 million hectares to 2.4 million hectares accordingly and is shown on composite map in Fig. 6(g).

4. Conclusions and discussions

Small-scale irrigation is regarded as a promising option to improve the agricultural sector in Nigeria. This paper presents a study to evaluate the potential of expanding small-scale irrigation in the country. We incorporated our crop-specific knowledge of agricultural production in Nigeria, on both biophysical and economic sides, into the assessment. Starting from assumptions on how irrigation could function in different crop production systems, we chose to apply different approaches to assess irrigation development potentials associated with different groups of crops

Under our baseline conditions specified in this study, it is estimated that there are about 1 million hectares of land in Nigeria suitable for expanding irrigation to produce rice and dry-season maize and dry-season vegetables, and the potential for expanding irrigation for rainy season crop production is estimated to be 0.65 million hectares. The two estimated irrigation potential areas account for 2.4% and 1.6% of arable land area in Nigeria, respectively. In spite of the small percentage, the potential of expanding small-scale irrigation in Nigeria is still substantial in view of the absolute the magnitude of the areas. On the other hand, sensitivity analysis indicates that the estimated small-scale irrigation expansion potentials are sensitive to the values of input parameters used for calculating economic cost-benefit of irrigation development. These results highlights the financial risks in irrigation investment.

The results of sensitivity analysis on nutrient input level serves as an example to demonstrate how the potential of irrigation expansion could be influenced by synergies between irrigation and other agricultural production technologies. The sensitivity of estimated small-scale irrigation potential to nitrogen fertilizer application rates revealed in the analysis implies the irrigation potential is not a static concept, but is contingent on levels of other inputs in agricultural production. The decision making of irrigation investment thus should be put in a broader context of agricultural development and coordinated with other efforts in enhancing the agricultural productivity.

Finally, as a caveat, it is worth noting that apart from uncertainties or limitations which have been discussed above, our study is also subject to other uncertainties/limitations:

Firstly, in our cost-benefit calculation only the economic benefits of irrigation directly associated with crop production are accounted for. However, empirical evidence shows that benefits by small-scale irrigation infrastructure is actually multi-faceted, including secure drinking water supply for human domestic use and livestock production (Van der Hoek et al., 2002; Senzanje et al., 2008).

Secondly, we did not take institutional factors into account into our assessment, whereas lack of institutional capacity has been identified as a main barrier of expanding smallholder irrigation in Sub-Saharan Africa (Shah et al., 2002; Meinzen-Dick, 2014).

Lastly, groundwater resources were not adequately handled in our assessment. While there were no hydrogeological criteria explicitly included in Taiwo et al. mapping analysis, it was found that the distribution of land area with irrigation suitability identified in their study is strongly associated with distribution of alluvium in riparian zones (Taiwo et al., 2010). Alluvial aquifers are most productive aquifers. So the mapped extent of irrigation potential area probably already covers the main area with groundwater irrigation development potential in Nigeria. However, there is a lack of capacity and data to perform national-scale hydrogeological modeling to evaluate the capabilities of these aquifers for water supply. Developing coupled hydrologic-hydrogeological models to inform groundwater assessment constitutes an ongoing important research topic (Sutanudjaja et al., 2014; De Graaf et al., 2015). In our study, we chose to use dry-season runoff as resources constraints in the crop optimization of dry-season analysis. This possibly serves

as a conservative estimate of quantity of water resources which could be used to support irrigation development and therefore tends to leads to a conservative estimate of irrigation development potential. On the other hand, in the rainy season analysis, we did not impose water resources constraints given the uncertainty with groundwater resources abundance. The reported results probably overestimate the irrigation development potential in rainy season.

It would be interesting to extend the methodological framework in this study to incorporate these considerations in future work when data and appropriate quantities analytical methods are available.

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Appendix A. Supplementary data

Supplementary data associated with this article can be found, in the online version, at http://dx.doi.org/10.1016/j.agwat.2017.08.020.

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