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Irrigation and irrigated agriculture potential in the Sahel: The case of the Niger River basin

Prospective review of the potential and constraints in a changing climate.

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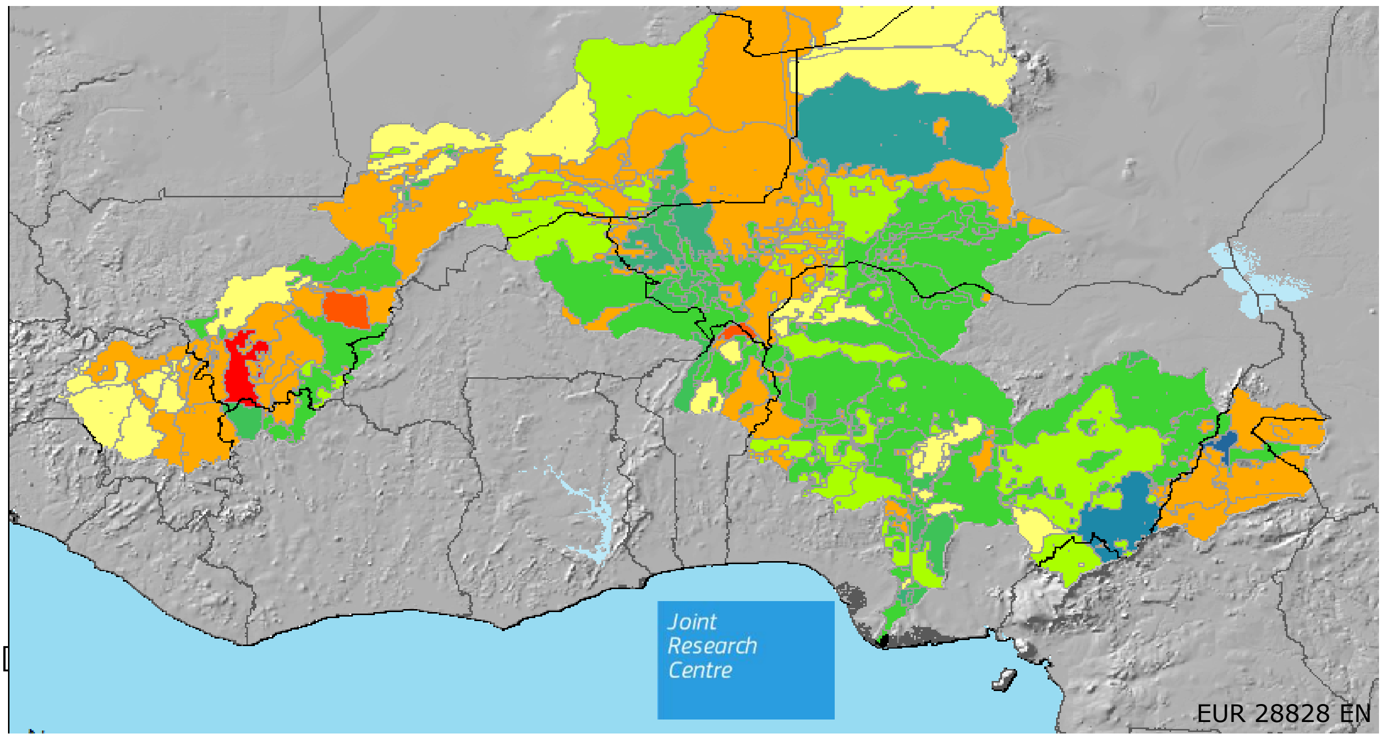

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Abstract

The report assesses the potential of developing irrigation in the Niger River Basin under various agricultural scenarios accounting for biophysical and socio-economic variables, and for expected climate change.

Irrigation potential is assessed in two parts. The first reviews recent literature in English and French (2010 onwards) on sustainable irrigation potential in the Sahel (i.e. Lake Chad basin, Niger, Senegal Volta River basins). Sahel agriculture possesses a significant irrigation potential. However, estimates fluctuate greatly depending on the scale of irrigation schemes, whether the resource is surface or ground water, expected and actual irrigation costs but also on determinants of success of irrigation schemes, including the varying effects when interacting with other inputs, such as fertilisers. Past, and not always successful, efforts were based on large public irrigation schemes (i.e. river dams and related canals). In a growing number of contexts, investments in small and micro-irrigation systems are identified as more desirable than conventional large schemes. Existing small-scale irrigation systems in the region are known to be developing however limited systematised evidence exists. The realisation of this potential is very sensitive to the costs of irrigation, among the highest in the world, with some technologies more sensitive than others (i.e. small river diversions). Moreover, irrigation potential is influenced by synergies among irrigation and other agricultural production technologies – it is maybe worthwhile to recall that irrigation potential is not a static concept, but it is contingent on levels of other inputs. Hence, irrigation investments need to be put in the broader context of productivity enhancement, rural development efforts and global changes such as urbanisation

The development of irrigation in the Sahel and in the Niger River basin in particular is a key intervention area for agriculture and development policy in general. Current policy identifies irrigation development as an instrument fostering food security. However, from the angle of optimization, rainfed agriculture retains the larger potential for development when looking at costs and overall potential profits. Moreover, support to the development of irrigated agriculture needs to be fully integrated with a relevant and adapted support to agriculture in general, particularly with regards to how it mitigates risk. Access to irrigation is expected to expand farmers' production opportunities. It mitigates production risks, even in low quantities as crop-saving irrigation. By reducing risk, it encourages farmers to make more intensive use of inputs and land. Moreover, this dynamic effect is also influenced by the type of irrigation systems accessed. For example, the literature has identified that farmers which have some off-farm income are particularly interested in investing in agriculture if irrigation is made available, whereas other groups may be interested in improving first their access to credit for farm inputs with then a view on irrigation. How production risks are perceived need to be clearly identified so that the irrigation systems fostered can be seen as risk-reducing Functioning supply chains would also make irrigation more profitable as they reduce losses of potentially more valuable products from irrigated agriculture and enhance market access.

Recently, registered regional increases in groundwater storage have been associated to diffuse recharge, partially compensating for groundwater withdrawal associated with irrigation development. Hence, hinting at some level of sustainability in the use of groundwater for small-scale irrigation in the Sahel, despite the risks associated with salinization.

The second part focuses on the Niger Basin to assess and quantify its irrigation potential through modelling. The model uses static biophysical and socio-economic indicators in model optimising profits of mainly small holder farms under 4 possible agricultural scenarios with distinctive productivity levels. In general, the projected irrigated area does not evolve much between scenarios mainly because of high productions costs associated with increased

irrigation. Although irrigation potential is theoretically large, investing in both irrigated and rainfed input intensification offers the largest potential gains. The results for total irrigation potential in terms of farmed area are in the range of 0.6-09M hectares, from the estimated current 0.53M hectares of irrigated land under the most productive scenario in terms of agricultural yields. However, even the most yielding scenario results of the current study are significantly lower than previous estimates developed in the literature, and depend on assumed irrigation and input costs. The specific strengths of this new estimation are that of using input costs from recent agricultural surveys (i.e. LSMS-ISA) along with crop suitability maps. Its main limitation is that is does not distinguish between irrigation technologies and related costs, constraining estimates to a generic (gravity) irrigation. In turn, the expansion of agriculture is exogenously determined and does not depend upon the variables analysed.

1. Introduction

With the doubling of the population of Africa to about 2.13 billion individuals by 2050 (United Nations 2015), the continent is challenged by the need of a "great balancing act" between increasing and diversifying needs and available resources (Searchinger, Hanson et al. 2014).

Agriculture is a key component of the equation and although its productivity has improved since 1990s, it has done so just above demographic growth (Wiggins 2014).

The overall low productivity of African agriculture, and in particular that of the Sahel, has also been associated to a low proportion of crop land irrigated (2% in the Sahel), compared to other developing regions (Asia with 37% and Latin America with 14%) (FAO Aquastat and land (2016), 2011 data). The Sudano-Sahelian region is a good example of potential as high value production is associated with irrigated areas (58% of value of agricultural output) and still has untapped hydrological potential (Svendsen, Ewing et al. 2009). Sahelian river basins have significant undeveloped irrigation, fisheries, transport and hydroelectric potential with only 20% of their irrigation potential realised to date (World Bank, 2014). Recent estimation of potentials have identified small-scale projects as having higher internal rates of return than large scale dams, although having less area expansion potential (You, Ringler et al. 2011). Such small-scale schemes are developing rapidly in the region (Torou eta. 2013). Uncertainties surrounding the impact of climate change on rainfed agriculture have renewed interest in evaluating irrigation prospects in the region.

Access to irrigation is expected to expand farmers' production opportunities. It mitigates production risks, even in low quantities as crop-saving irrigation. By reducing risk, it encourages farmers to make more intensive use of inputs and land (Shah et al. 2013).

In addition, as a key factor in a strategy to foster input intensification of agriculture, the expansion of irrigation is now high in the regional development agenda (Faurès and Santini 2008; You, Ringler et al. 2011; Burney, Naylor et al. 2013), in line with the growing trend of support by aid agencies to agriculture in general (OECD 2014).

Accounting for this context, this study assesses the advantages and limitations of developing irrigation in the Niger River Basin under various agricultural scenarios accounting for biophysical and socio-economic variables. To provide context to this exercise, the report starts by reviewing the recent literature on sustainable irrigation potential in the Sahel, focusing on the Lake Chad basin, Niger, and Senegal Volta River basins.

Based on existing biophysical and socioeconomic models it estimated the potential for irrigation growth in the Niger River Basin (Mali, Niger and Nigeria sections) accounting for climate change.

2. Literature Review

This section provides a review of recent literature on prospects for sustainable irrigation development in the Sahel (Niger, Lake Chad, Volta and Senegal river basins, see Figure 1). The study draws on (secondary) data sources such as available databases, policy reports and academic literature.

2.1. Approach and overview of the literature

The main goal of this review is to provide an overview of recent literature (2010 onwards) on the potential of sustainable irrigation development in the Sahel (Lake Chad basin, Niger, Senegal Volta River basins). Key issues are:

- Studies and methods to assess the potential of sustainable irrigation development
- Distinction between large- and small-scale irrigation
- Relation between irrigation potential and nutrient management

For the review English and French academic publications, books, reports, policy papers, studies international organisations / banks (World Bank, AfDB, IWMI, IFAD, FAO) and internet sources have been used. The academic literature was carried out mainly using the Wageningen UR digital library (http://www.wageningenur.nl/en/Expertise-Services/Facilities/Library.htm). The main terms for the specific searches included "SSA and Sahel" and "irrigation", "irrigation potential", "agriculture", "future development", "climate change", "climate change adaptation", "land use change", "agricultural scenarios", "nutrient management", "Niger basin", "Chad basin", "Volta basin", and "Senegal basin". For French literature, additional key words used were "l'irrigation", "L'agriculture irriguée", "potentiel d'irrigation", "Sahel" "Afrique de l'Ouest", "secteur agricole", "gestion des eaux", and "changements climatiques".

Various studies have looked at the potential of irrigation development in the Sahel / West Africa, taking into account one or more of the aspects of land and water resources availability, irrigation technology, agricultural practices, existing infrastructure, and socio-economic aspects (demography, investment needs, policies, markets). Literature and web sources have been screened and prioritised based on the relevance and usefulness with regard to prospects of irrigation in the Sahel (Table 1).

Table 1: Assessment of relevant literature related to irrigation potential Sahel region

Reference	Regional focus	Large scale and/or small scale	Link to nutrient management	Remarks	Priority for this report
You et al., 2010 (IFPRI)	Africa, country level	-	No	Biophysical and socio-economic	Yes
Svendsen et al. 2009 (IFPRI)	Africa, country level	-	Yes	Performance baseline indicators for expansion	Partly
Xie et al, 2014	Sahel basins	Small scale	Partly (SWAT)	Potential expansion of 4 small scale technologies	Yes
Pastori et al., 2011	Africa, country level	Both	Yes, yield scenarios irrigation management and fertiliser	Not a thorough study but quick overview	Yes
Van Wart et al 2013	-	No	No	Comparison of different agro-climatic zones for yield gap	No
Burney et al. 2013	SSA countries	Only distributed irrigation	No	Short position paper on advantages distributed irrigation	Yes
Conijn et al 2011	-	No	-	Only rainfed. Looks at fertilisers, and socio-economic aspects	No
Ringler et al. 2013	No, global study for 3 main crops	No, looks at alternative technologies	Yes	Global study	No
Namara et al. 2011	Ghana	Yes	No	Irrigation typology and constraints for development	Yes
Oyebande et	Senegal, Niger	No	No	Looks at climate change	Partly

al. 2010	and Volta Basins			impacts	
Sebastian 2014	Africa all countries	No	No	Includes map on irrigated infrastructure	No (except map on current irrigation)
Giordano et al, 2012	Africa and India	Smallholder (AWM)	No	African small scale agriculture review	Yes partly
Garrity et al. 2010	Africa continental	No	No	Agro-forestry (evergreen agriculture)	No
Dittoh et al. 2010	Burkina Faso, Mali, Niger and Senegal	Micro irrigation	No	Analysis of micro irrigation technologies	Yes
Kadigi et al. 2010	Sub-Sahara	Both	No	Policy brief	Yes
Worldbank 2014 policy brief	Ethiopia, Malawi, Niger, Nigeria, Tanzania, and Uganda	No	Yes	Looks into detail at the use of inputs	Yes
Morris and Barron, 2014	Burkina Faso	No	No	Looks into the adoption of AWM practices	No
Mueller et al. 2012	Global	No	Yes	Closing yields gap looking at input	Yes
Altchenko and Villholth, 2015	Africa continental	Yes	No	Groundwater irrigation potential	Yes
Diouf et al 2014	Senegal	No	No	Climate change adaptation & policy	No
Barbier et al 2009	West Africa	-	No	Overview large investments in water infrastructure in West Africa	Yes
Barbier et al 2011	Sahel	Yes	No	(Qualitative) description of irrigation methods in the Sahel	Partly
IFAD 2011	Burkina Faso	Soil and water conservation	No	Information sheet Developing agriculture in the context of climate change in Burkina Faso	No
Torou et al 2013	South-western Niger	Small scale private irrigation	No	Possibilities for groundwater in Iullemmeden Basin, south-western Niger	No
IFAD, 2013	Niger	No	No	Lessons learned on adaptation to climate change and conservation of soil and water	No

ADB, 2011	Africa continental	Yes	No	African economies socio-economic outlook in fifty years' time (2060)	Partly
World Bank, 2013	Sahel	no	no	Transforming Agriculture in the Sahel: Risk assessment	Partly
KFW, 2010.	Niger basin	no	no	Resilience, climate change adaptation in the Upper and Middle Niger River Basin.	Partly
USAID, 2011.	Niger basin	No	No	Climate change in the Sahel and Niger Basin	Partly
World Bank, 2014	Nigeria	Yes	No	Transforming Irrigation Management in Nigeria	Yes
Agra, 2014	SSA	smallholder	Yes	Climate change & smallholder agriculture. Quantified fertiliser use per crop per country.	Partly
Géo Conseil, 2014	Niger	Both	weak	Biophysical with a focus on groundwater, highlighting the impact such resource may have on food security	Partly
Zorom et al. 2013	Burkina Faso	Both	Yes	Determinants and preferences of farmers regarding irrigation investments	Partly
Ibrahim et al. 2014	Sahel	Both	No	Sustainability of groundwater extraction is partially covered by diffuse recharge from crop land	No
Shah et al. 2013	SSA	Small scale private irrigation	Yes	By reducing risk, irrigation encourages farmers to make more intensive use of inputs and land	No
Nazoumou et al . 2016	Niger	Small scale private irrigation	Weak	Low-cost groundwater irrigation represents a long term solution to alleviate poverty and food crises	No
Xie et a;/ 2017	Nigeria	Small scale private irrigation	Yes	Potential irrigation linked synergies with rural development policies	No

2.2. Irrigation in the Sahel

2.2.1. Current state of irrigation

The Sahel sub-region is one of the most vulnerable regions of the world. Poverty is prevalent in the Sahelian countries (Burkina Faso, Chad, Mali, Mauritania, Niger, and Senegal). Agriculture is the most important sector and is the principle source of livelihood for majority of the people. The performance of the agricultural sector is, due to its high exposure to risks, very variable.

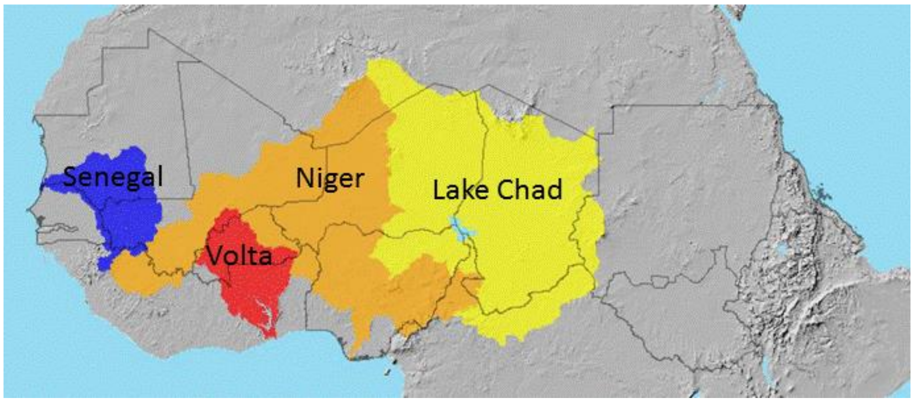


Figure 1: Focus area for the literature review: Niger, Lake Chad, Volta and Senegal basins. Source: river basins from HydroSHEDS[1], country boarders from GAUL, Hillshade based on GTOPO30.

Food production is Sub Saharan Africa is almost entirely rainfed. The region is water-abundant but uses less than 2 per cent of its total renewable water resources. Only 4 per cent (6 million ha) of the region's total cultivated area is equipped for irrigation. It is far from achieving the irrigation potential, which is estimated at 42.5 million ha (Kadigi et al., 2012). In addition, soils of sub-Saharan Africa are the most degraded in the world (AfDB, 2011).

In the Sahel, about 20 percent of its irrigation potential has currently been developed (World Bank, 2014). The Niger, Senegal, Lake Chad, and Volta River basins have tremendous undeveloped irrigation, fisheries, transport and hydroelectric potential. Although the region has some of Africa's largest aquifers, for the most part they are under-used.

Irrigation investments in the Sahel are concentrated in North Nigeria, the Office du Niger in Mali and the Delta in Senegal. Hydraulic infrastructure such as dams is not well developed in West Africa. There is great potential for large dams in the rivers Senegal and Niger (Barbier et al., 2009). The World Bank is calling for more large-scale irrigation in the Sahel to help the region to move towards resilience, embracing climate smart agriculture (World Bank, 2013). Efforts to manage water and to make it available where it is most needed are hampered by the lack of well-developed institutions for irrigation, the prevalence of subsistence farming, and high investment costs. FAO studies revealed that investment costs for irrigation in West Africa are among the highest in the world (Barbier et al., 2009). For long, the returns on investments have been low but these have slowly improved since the mid-1990s. For example, Kadigi et al (2012) looked at an IWMI study by Inocencio (2007), where costs and benefits for new irrigation projects are compared. An improvement in Economic Internal Rate of Return (EIRR) is seen which can mainly be contributed to by reduced costs and improved project performance.

[1] Lehner et al., 2008: New global hydrography derived from space borne elevation data. (http://www.hydrosheds.org/)

Table 2: EIRR of new construction irrigation projects (source: IWMI)

	1960s	1970s	1980s	1990s
South Saharan Africa (SSA)	-	6.1	7.8	25.5
Non SSA	12.8	14.8	13.0	17.3

The best available evidence of the benefits of irrigation in the region are estimates that irrigated agriculture is between 1.5 and 3 times as productive as rainfed agriculture, and, perhaps most importantly, studies of the socio-economic benefits of irrigation at the community level have documented significant contributions to poverty reduction (Kadigi et al, 2012).

Several initiatives are launched to tackle food, climatic, and security vulnerabilities, such as the Sahel Initiative from World Bank (2013) to build resilience and promote economic opportunity. The initiative is supported by the Governments of Burkina Faso, Chad, Mali, Mauritania, Niger, and Senegal who recognise the potential contribution of agricultural water to poverty reduction and growth. The initiative is coordinated by the CILSS (Interstate Committee for Drought Control in the Sahel).

The Sahel region produces and exports irrigated vegetables but its industry is weakly structured, and rice remains the main irrigated crop. Water use efficiency is low in the Sahel region, and surface irrigation is the main applied irrigation technology. Table 3, Table 4 and provide some statistics on irrigated areas and irrigation potential. Table 3 confirms the dominant position of Mali, Niger and Senegal with regard to the development of formal irrigation in the Sahel.

Table 3: Areas equipped for irrigation and irrigated areas (Aquastat, accessed 4 December 2015)

Country	Area equipped for irrigation (1000 ha)	Actual irrigated (1000 ha)	Irrigation potential (1000 ha)	% of irrigation developed
Mauritania	45.01 (2004)	22.84 (2004)	250	9 %
Burkina Faso	54.27 (2011)	46.13 (2011)	233.5	19 %
Mali	371.1 (2011)	175.8 (2000)	566	31 %
Niger	99.89 (2011)	87.87 (2010)	270	32 %
Senegal	119.7 (2002)	69 (1997)	409	17 %
Nigeria	293.2 (2004)	218.8 (2004)	2100	10 %
Chad	30.27 (2002)	26.2 (2002)	1200 a 5000	2 %

Among the basins, the Niger stands out as one of the most important one in Africa with a large potential for infrastructure development, including a four-fold expansion of irrigation (World Bank, CIWA in the Niger Basin, 2014, FAO 1997, FAO, 2005). Existing estimates indicate that between 1-5% of the total crop area in the basin is irrigated (0.55-0.9 M ha). In turn, irrigation potential could reach 1.5-2.9M ha with an associated expansion of the total agricultural area (ABN & BRL 2007; FAO 1997; FAO 2005)

Table 4: Irrigation potential for Sahelian Basins (source: FAO, 2005)

Basin	Irrigation potential (1000 ha)
Niger Basin	2.816,5
Lake Chad Basin	1.163,2
Senegal Basin	420
Volta Basin	1.487
Africa continent total	42.500

Table 5: Irrigation potential of the Niger River basin

Country	Irrigation potential (1000 ha)
Guinea	185
Côte d'Ivoire	50
Mali	556
Burkina Faso	5
Benin	100
Niger	140

More recent estimates gathered from the literature review offer a much contrasted picture in terms of potential, not all comparable given their different resources and scope.

Table 5: Irrigation potential of the Niger River basin. estimated after 2010.

Water resource	Increase in irrigated area (1000 ha)		Area	Source
	Large Scale	Small Scale		
All water sources	1619, excluding protected areas	1265, excluding protected areas	Soudano-Sahel	You et al. 2011
		8450	Soudano-Sahel	Xie et al. 2014
Only ground water		[1070-2060], depending on environmental recharge needs	Soudano-Sahel	Altchenko and Villholth, 2015
		[1000-14000], depending on the intensity of usage	Burkina-Faso, Mali, Niger	Pavelic et al. 2013

2.2.2. Water resources and climate change

Climate change and vulnerability

The Sahelian river basins are particularly vulnerable to climate change and variability, as farmers depend on water from the river. The vulnerability is further increased by the fact that most agriculture is rainfed (KfW, 2010). Weather extremes are likely to increase the pressures on agriculture in the region (World Bank, 2013). Global climate models do not agree on whether the Sahel region is likely to become wetter or drier over the course of the 21st century (USAID 2013). Around half of the models used by the IPCC predict increased rainfall, while the other half predict decreased rainfall. Nonetheless, predictions of wetter conditions in the central and eastern Sahel (including the portion of the Niger Basin within Niger) and drier conditions in the western Sahel (the Guinea highlands and source of the Upper Niger) are compatible with recent observations. The UN Environment Programme (UNEP) says most climate models for the Sahel do predict drier conditions for the future. IFAD (2013) looked at different models to identify the effects on agricultural production as a result of yield changes in the Sahel. Climate projections models tested by CGIAR (2008) and IFPRI (2013) are compared. The models show a stable or increase in precipitation, and for temperature, an increase is seen, with values depending on the region. For effects to agricultural production as a result of yield changes, it is seen that the agricultural season and cultivable area differ for the scenarios. Projections from CGIAR (2012) forecast a 5-25% reduction in rainfed sorghum yields by 2050 for a large part of Niger. According to the IPCC scenarios, the Nigerian Sahelian band should experiment a shortening of the length of the agricultural season by 20% by 2050 and a 50% reduction in rainfed agriculture yields by 2020.

Temperatures in West Africa and particularly in the Sahel have changed somewhat faster than the global warming trend (ECOWAS-SWAC/OECD/CILSS, 2008). There is strong consensus that in the coming decades, continued climate change will result in more unpredictable weather accompanied by temperature rise in the Sahel. Climate experts predict temperature rises of 3-5°C by the middle of the century, and it is warned for that West Africa's Sahel region could see millions of 'climate refugees' (Thomas, 2013). Schlenker and Lovell (2010) analysed yield response to climate change for several key African crops and found considerable aggregate production changes in Sub Saharan Africa. They also found that African countries with the highest average yields have the largest projected yield losses, suggesting that well-fertilised modern seed varieties are more susceptible to heat related losses. The GAEZ v3.0 crop model results that are being used in this study use different crop varieties under different input levels (e.g. traditional crop varieties for low input levels and high-yielding varieties for high input levels (IIASA/FAO, 2012). See also paragraph 3.1.7.

For the Sahel countries, national and regional policies emphasise the importance of irrigation development (e.g. CAADP, NEPAD) to adapt to climate variability and to improve food productivity. World Bank (2013) formulates a massive scaling-up of irrigation investments as one of the core interventions for a sustainable approach to agriculture in the Sahel.

Underutilised potential of groundwater

The Sahel region faces limited natural precipitation. However the region has significant levels of both ground and surface water. It is reported that in Niger, which is probably the most arid country in the sub-region[2], has a groundwater stock of about 2000 billion cubic meters and surface water from the River Niger and many small dams and rivers are yielding

[2] Niger has e.g. the lowest national rainfall index NRI (FAO) and the most recorded drought events for West Africa with the largest number of people affected (EM-DAT International Disaster Database, 2014).

about 30 billion cubic meters of water annually (Woltering et al. 2009). Similarly, Burkina Faso, Mali and Senegal abound in both groundwater and surface water. The potential for irrigated agriculture in the Sahel is very large and groundwater irrigation is seen as a solution for Sahelian farmers, especially as an adaptation strategy to address climate variability and soil fertility reduction.

Regional increases in groundwater storage have been recently associated to diffuse recharge (Ibrahim, Favreau et al. 2014; Nazoumou, Favreau et al. 2016). This phenomenon partially compensates for groundwater withdrawal associated with irrigation development, hinting at some level of sustainability in the use of groundwater for small-scale irrigation in the Sahel, despite the risks associated with salinization (Ibrahim, Favreau et al. 2014).

2.3. Prospects for irrigation development

2.3.1. Definition of irrigation potential

For describing the aspects of irrigation potential, the following definition has been taken from FAO (1997):

'The area which can potentially be irrigated depending on the physical resources 'soil' and 'water', combined with the irrigation water requirements as determined by the cropping patterns and climate. In this study it is called 'physical irrigation potential'. However, environmental and socio-economic constraints also have to be taken into consideration in order to guarantee a sustainable use of the available physical resources. This means that in most cases the possibilities for irrigation development would be less than the physical irrigation potential.'

The reviewed studies assess the potential for irrigation in different ways –considering the (ground) water resources available for irrigation, or by considering (ground) water availability and available land, or including socio-economic aspects, environmental aspects, and so forth. The next section elaborates on these definitions.

2.3.2. Key studies and methods to assess irrigation potential

An overview of the identified key studies for irrigation development in the Sahel and their outputs is given in Table 6.

Table 6: Key references on irrigation development, methods and output for each study

Reference	Methodology used	Irrigation technology focus	Regional focus	Output from study and relevance
Scientific papers/reports				
You et al. 2011 (IFPRI)	Biophysical and socioeconomic approach, in 5 steps: 1) Estimates area and yield distributions on a 1 to10 km resolution global grid 2) Calculate runoff 3) Identify potentially irrigable area based on topography 4) Maximise annual net revenue due to irrigation expansion 5) Calculate internal rate of return	Large scale and small scale	Africa as a whole, it's countries and grouped as agro-ecological zones	Identifies countries with largest potential for irrigation expansion. Quantifies large, dam-based and small-scale irrigation investment for African countries based on agronomic, hydrologic, and economic factors. This type of analysis can guide country- and local-level assessment of irrigation potential.
Xie et al. 2014	Integrated modelling system that combines GIS data analysis, biophysical and economic predictive modelling (SWAT< DREAM) and crop mix optimisation techniques. Includes IWMI scenarios on how agricultural production systems can be reshaped by smallholder irrigation.	Smallholder irrigation (motor pumps, treadle pumps, communal river diversion, and small reservoirs)	Sub Saharan Africa split into 4 regions (Central Eastern, Gulf of Guinea, Southern, and Sudano–Sahelian)	Irrigation expansion potential for smallholder technologies. Two types of results are shown: -Expansion potential baseline conditions (baseline commodity price and cost values). -Expansion potential with alternative irrigation costs and crop prices.
Burney et al. 2013	Review of distributed irrigation systems across sub-Saharan Africa	Small-scale (distributed systems)	Sub-Saharan Africa	Short position paper with advantages of distributed irrigation
Pastori et al 2011	GISEPIC AFRICA: GIS integrated with a biophysical model (EPIC) to simulate impacts of nutrient and water limitation on crop production. Fertilisation input data derived from the FAO FERTISTAT.	Not irrigation technology but water management scenarios, incl. nutrients	Continental Africa, case study Northern Africa	-Map of actual and potential irrigation areas for different scenarios. -For all African countries, indication if crop limitation is N limited or Water limited.
Pavelic et al 2013	Generic groundwater balance–based methodology	Smallholder irrigation using groundwater	13 focal countries: Burkina Faso, Ethiopia, Ghana, Kenya, Malawi, Mali, Mozambique, Niger, Nigeria, Rwanda,	Potential expansion of irrigation for smallholder groundwater irrigation for 13 focal countries in Africa (estimating the upper limits for groundwater irrigation potential)

			Tanzania, Uganda, Zambia	
Altchenko and Villholth, 2015	Annual groundwater balance approach using 41 years of hydrological data (Following the approach of environmental needs by Pavelic et al. 2013). Recharge data from PCR-GLOBWB global hydrological model.	Not technology but irrigation potential per grid from renewable groundwater (water balance approach)	Africa wide (cells, 0.5 spatial resolution)	Africa continent wide map of GWIP (groundwater irrigation potential), indicated in terms of fractions of cropland potentially irrigable with renewable groundwater. Takes into account environmental needs.
Pavelic et al 2012	Generic groundwater-balance-based methodology for estimating sustainable groundwater irrigation supplies. Also assess how cropping choices influence the potential areal extent of irrigation.	Small scale, groundwater potential	Two case studies: basin in Niger and basin in Ghana/Burkina Faso.	For 2 case studies, the potential irrigated area is estimated based on groundwater availability.
Namara et al 2011	A typology of irrigation systems in Ghana was developed (classification of types). For each type, the management structure and the costs and returns are quantified, after this the future prospects for the different types of irrigation are described.	Both large scale and small-scale	Ghana	Policy recommendations for irrigation in Ghana; Description of opportunities and constraints of the various irrigation typologies (qualitative), a.o. about management structure.
Oyebande et al 2010	Synthesis of state of art research regarding climate change impact on water resources in West African sub-region using basins of Senegal, Niger and Volta basins.	Irrigation in general, and impacts of climate change	Senegal, Niger and Volta Basins	Description of climate change impacts (however results show mainly uncertainties and complexities in the climate change research, and also uncertainties associated with the impacts of future climate changes on water resources)
Dittoh et al 2010	Analysis of micro irrigation technologies in Burkina Faso, Mali, Niger and Senegal (famer's perception and profitability analysis of micro irrigation, suitability of public private partnerships)	Micro irrigation	Burkina Faso, Mali, Niger and Senegal	Suggestions for future direction for irrigation development in the West African Sahel based on profitability analysis micro irrigation
Mueller et al 2012	Study potential changes in irrigated area and nutrient application needed to close yield gaps of maize, wheat and rice using input–yield models. Agricultural intensification scenarios.	Nutrient and water management for closing yield gap	Global study	Provides indication of management changes necessary to achieve increased yields.\, at global level. It shows whether yields are nutrient and / or water limited.
Mac Donald et al 2012	Production of maps of aquifer storage and potential borehole yields based on national hydrogeological maps	Aquifers	Africa continental	Quantitative maps of groundwater resources in Africa (first quantitative maps of groundwater for Africa..). Maps produced are groundwater storage, depth of groundwater, and aquifer productivity (borehole yields).

Barbier et al, 2009	Overview of large scale irrigation investments in West Africa, including overview of costs	Large scale	West Africa	Provides info on potential of the great rivers Senegal, Niger and for large dams
Other: Policy briefs, NGO's etc.				
Kadigi et al 2010	Review of literature on Sub-Saharan African irrigation schemes; Case studies and interviews with policymakers and other stakeholders	Key success factors of irrigation	Sub-Saharan Africa	Policy brief on major challenges in irrigation and highlight both successes and failures
Giordano, 2012 (IWMI)	Review of practices in Africa (Burkina Faso and Ghana) and India	-	Africa	Future prospects of smallholders AWM and institutional setting
Worldbank. 2014	Irrigation development plan (rehabilitation, dam operation, institutional, value chains)	Investments needs	Nigeria	Transforming irrigation management plans (rehabilitation, institutional strengthening)

A short summary of for each of the findings is available in Appendices.

2.3.3. Key topics emerging from the review of irrigation potential estimates

The literature review presents irrigated agriculture in the Sahel with a large potential for growth. This stems primarily from the abundant natural resources (water and land), and the large yield gap to increase food security and reduce poverty. Key issues that affect irrigation potential are land and water availability and socio-economic aspects. Irrigation potential and performance are influenced by synergies between irrigation and other agricultural production technologies.

Access to irrigation is expected to expand farmers' production opportunities. It mitigates production risks, even in low quantities when as crop-saving irrigation. By reducing risk, it encourages farmers to make more intensive use of inputs and land. Moreover, this dynamic effect is also influenced by the type of irrigation systems accessed. From their 1550 households strong survey across nine SSA countries, Shah et al (2013) concluded that irrigation "on-demand" fosters turning part or all farming towards high-value crops. Lift elevation irrigation is strongly associated to this type of high-value, market orientated crops, in contrast to gravity irrigation which tends to be associated to crops for both subsistence and market. Motor-pump irrigation was favoured by many farmers, and although it may not systematically translate in higher productivity than alternative systems, it inspires confidence in farmers to intensify more, with greater risk and to open up to the market (Shah, Verma et al. 2013).

The most comprehensive approaches have been provided by You et al (2010), Xie et al (2014) and Burney et al (2013), which take into account land, water and socio-economic variables for estimating the irrigation potential:

- You et al. (2010) quantified irrigation potential and investments costs at country level, for both large-scale and small-scale irrigation, at positive internal rate of return (IRR) levels (Table 19). In terms of country potential, Nigeria stands out as having particularly great potential for both large- and small-scale schemes. Mali stands out as a particularly lucrative site for small-scale irrigation investments. In general, adding large-scale irrigation to dams in need of rehabilitation appears more profitable than either operational or planned reservoirs. This is largely due to the high returns in Nigeria. Comparing profitability of small-scale and large-scale irrigation potential, the results present a striking contrast. IRRs are considerably higher for small scale irrigation expansion. You et al. (2010) found for the Sudano Sahelian region, that the potential for irrigation expansion through small-scale schemes amounted to 1.3 million ha, with an estimated IRR averaging 43%. For large dam-based projects, by contrast, the comparable figures were 1.6 million ha potential and an IRR of 8.6%. Thus, according to this study, small-scale irrigation offers much greater potential profits.
- Xie et al. (2014) quantified the potential for profitable smallholder irrigation expansion in SSA and the Sudano-Sahelian region[3]. The area expansion potential in the Sudano–Sahelian region is 3 million ha for motor pumps, 2.3 million ha for treadle pumps, 1.1 million ha for small reservoirs and 2 million ha for communal river diversions. Since this is not done at country level, its numbers cannot be compared to the findings for smallholder expansion potential of You et al. (2010). Several scenarios with different (alternative) costs are used. When taking into account alternative costs, it can be seen that the estimated irrigation expansion potential is highly sensitive to irrigation costs and

[3] Including Burkina Faso, Chad, Eritrea, Mali, Mauritania, Niger, Senegal, Somalia, Sudan and The Gambia

crop prices. The final expansion potential should include irrigation technology costs and commodity price developments.

- Burney et al. (2013) describe similar findings for the advantages of smallholder irrigation as indicated by You et al. (2010). Small-scale distributed irrigation has larger expansion potential than large centralised schemes and offers much greater potential profits. This potential of small-scale irrigation is confirmed by Giordano 2012 (IWMI), indicating a trend towards individual and community-managed schemes. This is due to the low performance and limited extent of public irrigation schemes. They provide a map of the potential of expanding mortised pumps in SSA, taking river basin hydrology, environmental constraints, yield improvements, investment costs and price impacts of expanding crop production into account, the map identifies locations with potential to expand the number of motorised pumps.

Other studies have looked at the untapped potential of groundwater in the Sahel which is an indication for irrigation potential:

- Pavelic et al. (2013) provide estimates of smallholder irrigation potential at country level based on simplified estimates of the availability of groundwater resources. For the Sahel region, for the countries Niger, Nigeria, Mali, and Burkina Faso estimates are provided showing medium to high potential for the Sahel region (Table 21).
- Altchenko and Villholth (2015) provide a map for Africa of groundwater irrigation potential, indicated in terms of fractions of cropland potentially irrigable with renewable groundwater. For three different levels of environmental flows, the area is estimated (Table 22). This shows that significant irrigation potential exists for smallholder irrigation based on groundwater availability in the semiarid Sahel which could support poverty alleviation if developed sustainably and equitably. The values are comparable to the irrigation potential for smallholder irrigation as quantified by You et al. (2010), but it is difficult to compare because of the variation in environmental flow.
- Pavelic et al. (2012) looked at groundwater availability for two cases (Niger and Ghana/Burkina Faso) which show significant potential for further groundwater development for irrigation expansion. The lesson from both case studies is that the untapped development potential may be realised with sufficient understanding of the demand-and-supply balance. It also shows that in almost all practical cases, groundwater availability will restrain irrigation development rather than land area.

The links between irrigation typology (i.e. management of schemes) and irrigation potential is also studied:

- Namara et al. (2011) show that the irrigation potential for Ghana is huge, however estimates of the irrigation potential diverge wildly. There is a strong argument to encourage private sector investment rather than continuing to sink public funds in poorly operated and maintained public irrigation schemes.
- A better performance of more independently owned schemes is confirmed by others such as Ofusu et al (2012) and Dittoh et al. (2010). Dittoh et al. (2010) suggest micro irrigation operated by farmers as a future direction for irrigation development in the West African Sahel. Their study shows that micro irrigation in the Sahel (incl. Burkina Faso, Mali, Niger and Senegal) is profitable to farmers and has higher impacts. The cost of establishing a viable smallholder drip irrigation system is however above the capabilities of small farmer groups. The study recommends instituting modified public-private partnership (PPP) methodologies of funding and management of farmer-group (micro) drip irrigation systems to ensure viable and sustainable systems in the Sahel.

Irrigation potential is influenced by synergies between irrigation and other agricultural production technologies. Irrigation potential is not a static concept, but it is contingent on levels of other inputs, such as nitrogen fertilizer, in agricultural production. Hence, irrigation investments need to be put in the broader context of productivity enhancement and rural development efforts (Xie, You et al. 2017) and global changes such as urbanisation (Barbier et al. 2011). It is important to highlight that West Africa stands out as hotspot of nutrient limitation, and the effects to irrigation performance is captured in various studies:

- In their typology of farmers with regards to adaptation strategies to shocks, Zorom et al. (2013) identified that those farmers which have some off-farm income are particularly interested in investing in agriculture if irrigation is made available, whereas other groups may be interested in improving first their access to credit for farm inputs with then a view on irrigation. How production risks are perceived need to be clearly identified so that the irrigation systems fostered can be seen as risk-reducing (Burney and Naylor 2012; Burney, Naylor et al. 2013).
- Pastori et al. (2014) addresses the link between nutrient management and irrigation performance, who found that the main factors limiting crop production are nutrient and water inputs. The study at continental scale by comparing the current management scenario with two more productive ones, showed how the expected potential increase of crop production in Africa is strictly linked with fertilisation in irrigation.
- Similarly, Mueller et al. (2012) found that yield variability is heavily controlled by fertiliser use, irrigation and climate. They analysed yield gaps and showed that crop production in the Sahel region is mostly nutrient limited.
- The role of fertiliser use in irrigation productivity is further analysed by Ofusu et al (2012) for the White Volta (northern Ghana and southern Burkina Faso). They looked for a comparative analysis of productivity in terms of crop yield, water use and financial returns. The results show that adequate fertiliser application is the major contributor to irrigation productivity. The impact that an irrigation technology has on the irrigation productivity has got to do with the control over the water resources by the farmer and the size of the farm irrigated by the technology. Farmer driven technologies and endogenous irrigation development provides a strong way forward for governments to create policies that facilitate poor farmers becoming irrigation entrepreneurs.

2.3.4. Methods used

Agriculture in the Sahel is predominantly rainfed and irrigation is regarded as a required solution to boost levels of agricultural productivity. For a sustainable irrigation expansion, one needs to understand the locations and technologies with greatest potential for irrigation. In particular, information is needed about geographic, agronomic, and economic factors that need to be taken into account when assessing the long-term viability and sustainability of planned projects. The review has shown several approaches to irrigation potential assessment which together provide a good insight:

Several studies follow an integrated modelling approach in which hydrological and biophysical variables are taken into count (land and water availability, agronomy) as well as socio-economic aspects (costs, crop prices, internal rate of return), e.g. You et al. (2010) and Xie et al. (2014). By taking a close and combined look at agronomic, geographic, and economic characteristics of potential expansion sites, one can gain a better understanding of the conditions under which irrigation investments will yield their full potential. You et al., 2010 analysed the irrigation potential and investments needs for both large, dam-based and small-scale irrigation, taking into account the internal rate of return (IRR) on investments. Xie et al. (2014) looked at small scale irrigation potential for current conditions, but also at the expansion potential with alternative irrigation costs and crop prices using optimal solutions.

In other cases irrigation expansion potential is estimated based on water availability studies. Pavelic et al. (2012) apply a simplified methodological framework which uses groundwater availability to estimate irrigation potential (estimation of upper limits of groundwater development for irrigation in terms of volumes of abstraction and irrigated area). Here it is also assessed how cropping choices influence the potential areal extent of irrigation.

Finally, additional studies (also) take into account the irrigation technology and management of irrigation schemes (typology) and the local/institutional setting for the prospects for sustainable irrigation development (e.g. Namara et al 2011, Kadigi et al 2012).

2.3.5. Data availability

Several studies have reported uncertainties in the irrigation development assessment because of lack of reliable and adequate data in the region. Specifically, there is little quantitative information on groundwater resources in Africa, and groundwater storage is consequently omitted from assessments of freshwater availability. The region is characterised by scarcity of data and lack knowledge on groundwater systems. Little is known about the physical extent, accessibility and development potential of groundwater. There are very few groundwater systems in the Sahel where both the recharge and discharge components of the groundwater balance have been determined. The maps on groundwater storage produced by MacDonald et al. (2012) for the Sahelian countries are helpful as they are the first quantitative continent-wide maps of aquifer storage and potential borehole yields in Africa. These maps help to support the development of groundwater-based irrigation strategies.

Rainfall data form another vital element in regional or continental studies with an agro-ecological component. Although there are several global remote sensing based and/or modelled rainfall dataset available, only a very limited number of high quality observed rainfall data is available. Often the remote sensing based and/or modelled rainfall datasets can considerably differ, especially in Africa and the Sahel where calibration and validation is difficult because of the lack of observed rainfall data.

Irrigation development is a key investment priority for the countries in the Sahel. It is therefore important for future planning of irrigation that quality and accessibility of information is improved. This is also one of the goals of the Cooperation in International Waters in Africa (CIWA), who supports governments to unlock the potential for sustainable and inclusive growth, climate resilience, and poverty reduction by addressing constraints to cooperative management and development of international waters.

2.3.6. Implications and expected added value of this study

The findings from the literature review and implications for the scenario study in terms of methods and data to consider are:

- To understand the real irrigation potential for an area, assessments should include land, water and socio-economic variables. The method proposed for the scenario study therefore uses an integrated approach where biophysical parameters and socioeconomic variables are combined to assess the irrigation potential. A partial equilibrium model is used to maximise outputs given a certain number of crops and technologies.
- The irrigation expansion potential is highly sensitive to irrigation costs and crop prices (Xie et al., 2014). In the scenarios study, specific attention is given to the pricing issue, including prices of inputs that are relevant too.
- Determinants of success for irrigation performance in the Sahel from the literature study are (secure access to) land and water availability, irrigation technology, stable access to input / output markets, effective institutions, and farmer involvement in operation and maintenance (Kadigi et al., 2012). In our study, these determinants are not taken into account. A future extension of the model could make these determinants part of the model.
- Small-scale irrigation offers larger potential profits than large centralised schemes, demonstrated by higher IRR (Internal Rate of Return) for small scale schemes (You et al., 2010). Small scale schemes also perform better than larger public schemes.

The influence of ownership of infrastructure and its link to the success of irrigation schemes is confirmed in various studies. This beneficial effect of ownership is not part of the modelling study but could be taken into account in a future extended model. Again, it is recommended to extend a future model with such ownership effect.

- Crop production in the Sahel region is mostly nutrient limited and the potential increase of crop production in the Sahel is linked with fertilisation (Pastori et al., 2014, Mueller et al., 2012). The literature study shows examples where the major contribution of adequate fertiliser application to irrigation productivity is quantified. Soil degradation in the Sahel is an issue that must be successfully addressed and is incorporated in the scenarios (chapter 6).
- The review revealed a large set of multiple scale data relevant for irrigation assessments, i.e. household level (socio-economic surveys), field scale (crops), irrigation scheme level (management), hydrological unit level (basin), and/or aggregated to land / water / administrational units depending on the purpose of study. For estimating the irrigation potential in this study, it is proposed to use homogeneous units for the model runs ("target spatial units"). This matches the Living Standards Measurement Study - Integrated Surveys on Agriculture (LSMS-ISA) (World Bank, 2017) scale at which the model has been calibrated (see chapter 6).

The literature study revealed datasets that are relevant for the scenario study and will be used as much as possible:

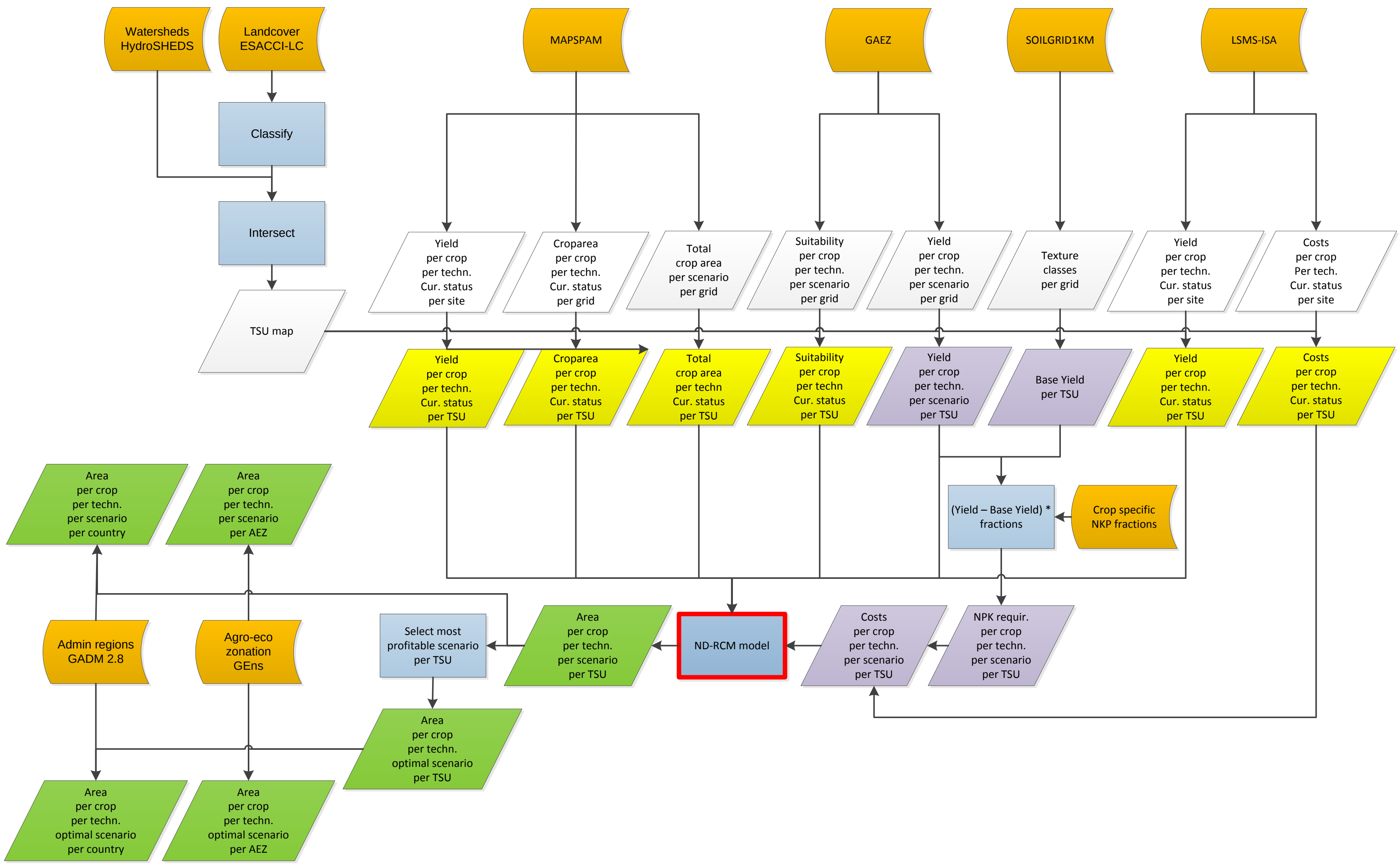
- Irrigation investments costs at country level (You et al, 2010);
- Crop prices (Xie et al, 2014) ;
- Cropping patters, crop yields (Ofusu et al., 2012, a.o.);
- Profitability of small-scale and large-scale irrigation (You et al, 2010);
- Availability of groundwater resources from various sources (Pavelic et al 2013, Altchenko and Villholth, 2015), maps on groundwater storage produced by MacDonald et al. (2012)

3. Methodology for estimating irrigation potential

This chapter describes the data and methodological section of the model. The method is based on You et al. 2011 and Xie et al. 2014 where biophysical parameters and socioeconomic modelling are combined to assess the irrigation potential. Given time and budget constraints the modelling approach in our study is more simplified where biophysical parameters - such as yield and input use per crop per technology - are not dynamically interacting with the socioeconomic result. The biophysical parameters serve as exogenous variables of the socioeconomic model that can be different per agricultural scenario. However, area specific production data on costs and yields were used here (LSMA-ISA) as more adapted and reliable source than previous exercises.

A serial, stepwise processing line is followed:

1. Define Agricultural Scenario's (AS's)
2. Define Target Spatial Units (TSU's)
3. Select the main crops per TSU
4. Build crop specific suitability maps
5. Estimate crop area per TSU, irrigation type and AS
6. Derive observed crop yield, crop prices, irrigation- and other costs per TSU, technology
7. Estimate yields per crop per TSU, technology and AS
8. Estimate nutrient and irrigation requirement per TSU, technology and AS
9. Build and run the partial equilibrium model for each TSU and AS
10. Select most profitable AS per TSU
11. Aggregate results to AEZ and country resolution



Orange: external datasets; Blue: key processing step; Red outline: partial equilibrium model; White: intermediate results; Yellow: current status input data or reference data for calibration; Purple: scenario input; Green: Output.

3.1.1. Define Agricultural Scenario's (AS)

The following four agricultural scenarios are developed (see also chapter 4): Business as usual (BU), Medium Input Intensification (MII), High Input Intensification 1 (HII) and Extensification (EX).

Each of the 4 agricultural scenarios is described by elements to be used in the modelling. In chapter 4, the assumptions and justifications for the cited scenario elements are presented.

In its most elaborate form, the suggested approach is to compare model results between the four agricultural scenarios under different climate change scenarios (CC's) for the year 2050. The AS-CC combinations are the overall scenarios. In the final implementation, only a single climate change scenario is used, namely the Hadley CM3 A1FI[4] developed by Hadley Centre (UK). This results in the following overall scenarios:

- BU-A1Fl
- MII-A1Fl
- HII-A1Fl
- EX-A1Fl

During development of the model, a reference dataset served to calibrate the model. The reference is considered as the current status where total crop area ($TotalArea_r$), crop mix, irrigation share ($Area_{i,j,r}$), yield ($Yields_{i,j,r}$) and costs are known. With the calibrated model, crop mix and irrigation shares are derived for the AS-CC combinations.

3.1.2. Define Target Spatial Units (TSU)

The total extent to be covered in this project is defined as the Niger River Basin (~ 2.275.000 km2).

[4] The A1 storyline and scenario family describes a future world of very rapid economic growth, global population that peaks in mid-century and declines thereafter, and the rapid introduction of new and more efficient technologies. Major underlying themes are convergence among regions, capacity building and increased cultural and social interactions, with a substantial reduction in regional differences in per capita income. (IPCC, 2001) The A1FI is the fossil intensive A1 scenario, hence sometimes seen as pessimistic.

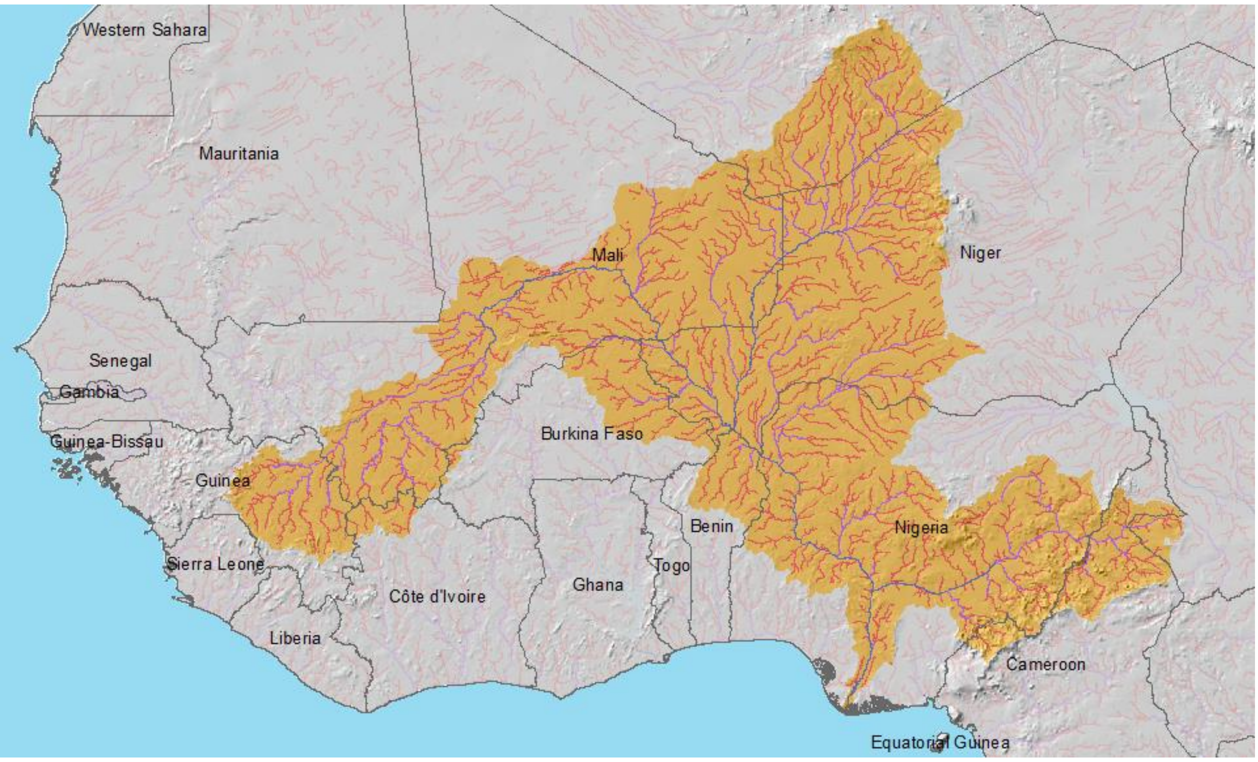


Figure 2: Niger River Basin and rivers. Source: HydroSHEDS, countries from GADM 2.8 and hillshade based on GTOPO30.

The TSU is the resolution at which the partial equilibrium model runs. Within a TSU the input-output data per crop for the partial equilibrium model are considered uniform (crop suitability, crop yield, irrigation requirement, NPK requirement, costs etc.). The TSU's are derived in such a way that the internal variation of input data is limited. Two external datasets are used:

- Watershed boundaries from HydroSHEDS[5] aggregation level 3
- Landcover, MCD12Q[6]

For the creation of the TSU's, the 16 original landcover classes were reclassified to 6 classes.

1. Forest
2. Woodland
3. Grassland/savannah
4. Permanent wetlands
5. Cropland
6. Barren sparsely vegetated.

Water bodies and settlements are treated as NoValue. Afterwards, an 8x8 majority filter was applied to reduce the "salt and pepper" effect. After reclassification, an overlay was made with the watersheds dissolved at the 3rd level and then rasterised. This resulted in 201 discontinuous TSU's within the Niger River Basin (Figure 3).

[5] Lehner et al., 2008: New global hydrography derived from spaceborne elevation data. (http://www.hydrosheds.org/)
[6] https://lpdaac.usgs.gov/

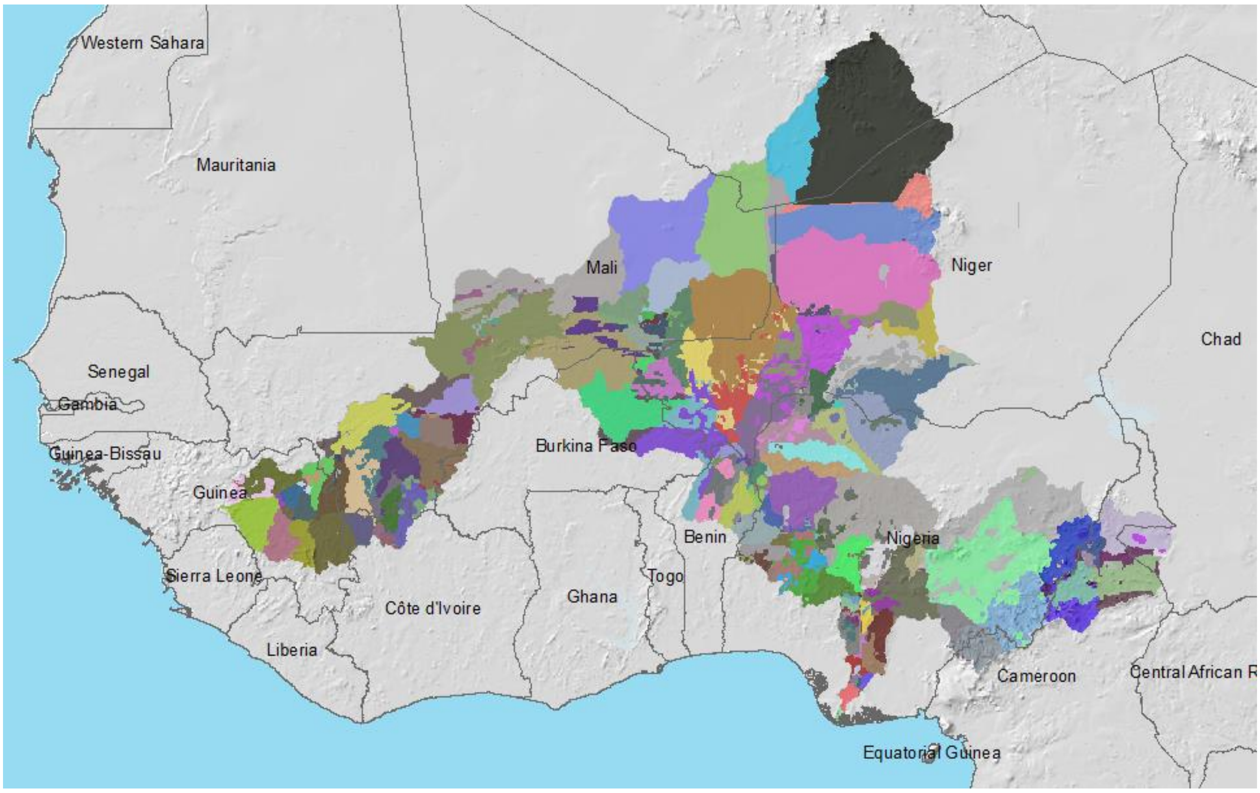


Figure 3: TSU's in the Niger River Basin based on HydroSHEDS and Landcover (MCD12Q). Background countries from GADM 2.8 and hillshade based on GTOPO30.

3.1.3. Select the main crops per TSU

The crop selection is based on the availability of input data in the region of interest (Niger River Basin). The most important datasets are

- GAEZ (44 crops/classes, see ANNEX II. GAEZ crop list)
- MAPSPAM (42 crops/classes, see ANNEX III. MAPSPAM crop list)
- LSMA-ISA (85 crops/classes, see ANNEX IV: LSMS-ISA crop list)

Cropdata/NPK fractions (28 crops/classes, see

- ANNEX V Cropdata crop list)

It was decided to take the MAPSPAM as the reference crop list and map crops of the other dataset to this list. With this strategy a conclusive overview is given of the irrigation potential per crop for each of the TSU's. By using an extensive list, each TSU will contain it's dominant crops.

3.1.4. Build crop specific suitability maps

The gridded Crop suitability index (value) of FAO GAEZ (Global Agro-Ecological Zone; category Suitability and Potential Yield / Agro-ecological suitability and productivity) is used to estimate crop suitability within each TSU. For their land productivity assessment, GAEZ matches crop growth cycle lengths with favourable temperatures conditions. Subsequently calculated potential yields are combined with climate reduction factors, soil and terrain conditions and take into account the level of inputs/management. To ensure that yields are achievable on a long term, fallow periods have been imposed (IIASA/FAO, 2012). Water availability is not taken into account at this stage of the GAEZ model[7]. Some soil related constraints that relate to irrigation systems are included (soil salinity and soil alkalinity (Fischer et al., 2002). Two technologies are distinguished: rainfed agriculture and gravity irrigation.

The following parameters were applied to select the datasets:

- Water supply: rainfed, Input level: low input level
- Water supply: gravity irrigation, Input level: intermediate input level
- Crop: all
- Time: baseline period 1961-1990
- Scenario: -
- CO2 Fertilisation: without CO2 fertilisation

This resulted in 82 suitability maps. For each of the suitability maps the average crop suitability index per TSU was calculated and combined into two tables:

- Av_Suit_IrrigatedGrav (average gravity irrigation suitability per crop per TSU)
- Av_Suit_Rainfed (average rainfed suitability per crop per TSU)

They are input for the partial equilibrium model and play a role in the substitution between crops and technologies under different agricultural scenarios (see paragraph 3.1.10.2).

3.1.5. Estimate total crop area per TSU and AS

To calibrate the partial equilibrium model, $TotalArea_r$ and $Area_{i,j,r}$ must be known. Ideally, these reference data are observations of the current status. The reference data are retrieved from MAPSPAM harvested area (You et al. 2014) and aggregated to TSU resolution ($Area_{i,j,r}$). MAPSPAM integrates GAEZ based suitability with official statistics over 2004-2006 to estimate harvested area per crop per technology on a grid resolution.

[7] In GAES Module VI, land cover data are used to derive actual yield and production estimates. The 'Digital Global Map of Irrigated Areas' (GMIA) version 4.01 is part of the land cover/land use categories used to distribute yields over 5 arc-minute gridcells.

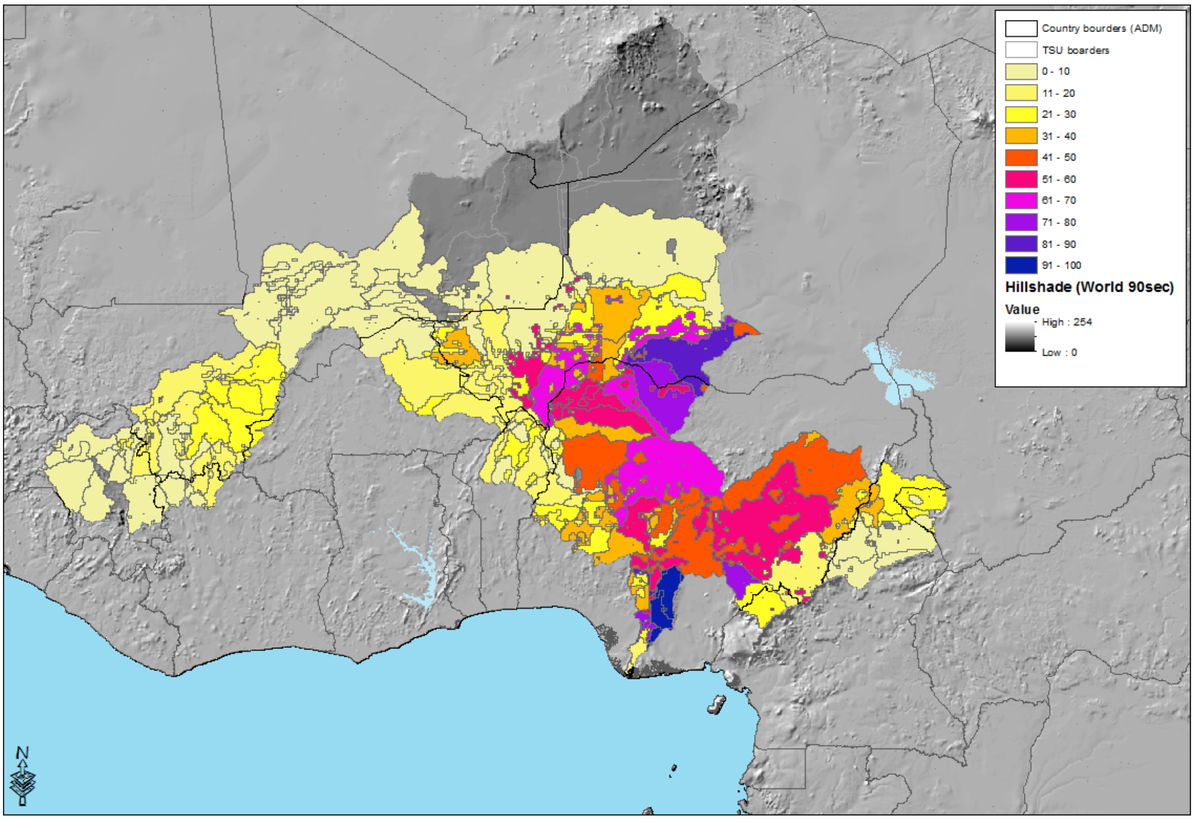


Figure 4: Mapspam total rainfed area as fraction of total physical area

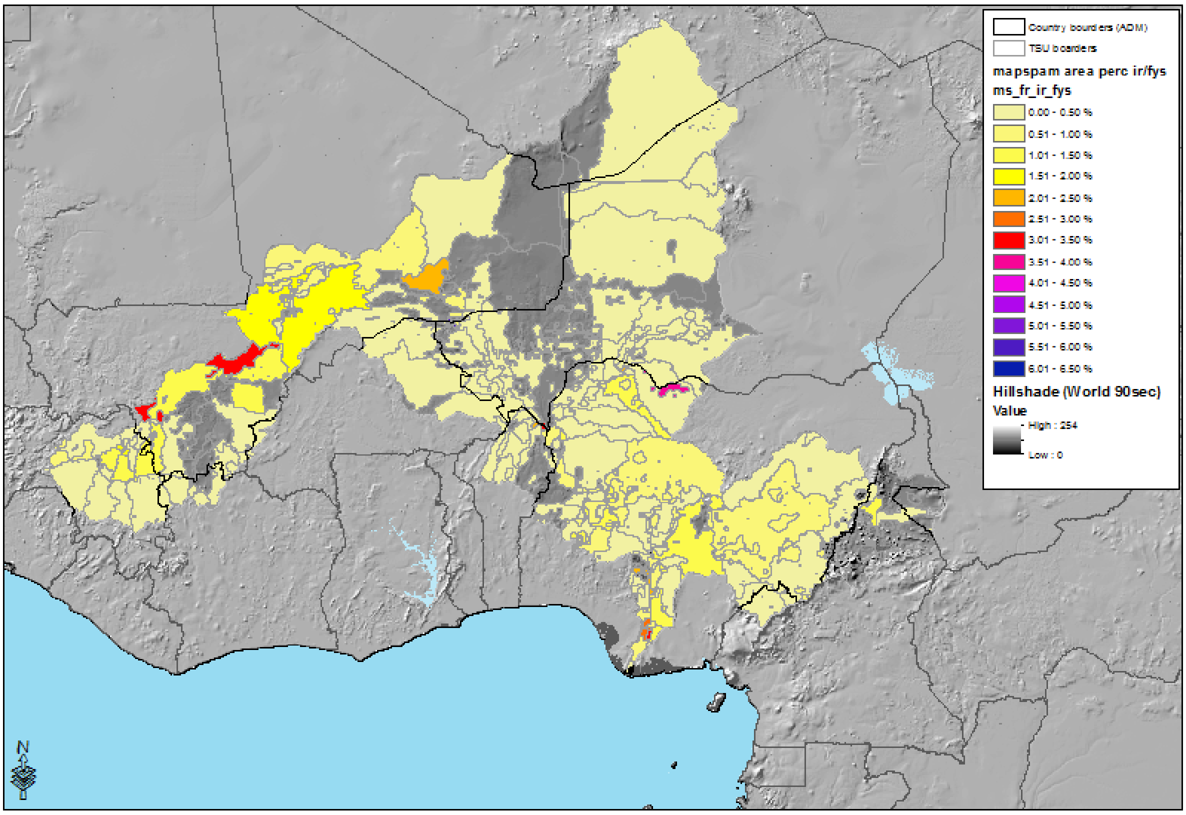


Figure 5: Mapspam total irrigated area as fraction of total physical area

In the scenario runs, $TotalArea_r$ per TSU remains an exogenous variable that influences the outcome of model and is different for the different agricultural scenarios (see also chapter 4). In scenario's MII and EX, area expansion is allowed up to 5% and 10% respectively. In the BU and HII scenario, area expansion is initially not allowed. In a sensitivity analyses, we analyse the effect of an addition allowed area expansion of 10% for the HII. The irrigation share and crop mix per TSU are output of the model ($Area_{i,j,r}$). Thus, $Area_{i,j,r}$ is endogenous in the scenario runs.

$Area_{i,j,r}$ multiplied with exogenous variable $Yield_{i,j,r}$ results in $Production_{i,j,r}$ which in turn is aggregated to total production per crop and cropgroup. In future model runs, area expansion can be adjusted for a specific scenario, leading to updated $Area_{i,j,r}$, updated $Production_{i,j,r}$ and updated total production in an iterative process; until a specific production target is reached. This is not part of the current study.

3.1.6. Derive observed crop yield, crop prices, irrigation- and other costs per crop per TSU per technology from LSMS-ISA data

The LSMS-ISA database (World Bank, 2017) was used to extract observed yields, prices and costs of the current status. As an alternative to the LSMS-ISA data, reference yields and fertiliser use per crop per technology per region could also be taken from GAEZ (crop model results). However, the data from crop models appeared quite incomplete resulting in missing yield and fertiliser data for quite some crops and technologies and extra assumptions to calibrate the model. Moreover, the advantage of the LSMS-ISA data for yield and fertiliser input, is the consistency with the other costs components that are all taken from LSMS-ISA database. GAEZ Yields per crop per technology per scenario are used as shifters of the reference values in the alternative scenarios (see paragraph 3.1.7 and 3.1.8.1).

The database presents plot or household level information on agricultural and socio-economic topics. The information from the LSMS-ISA database relevant for this study is presented in Table 7. For each TSU, a weighted average of the included indicators is calculated, based on the cultivated area. For some spatial units, there may not be sufficient observations. In such cases, information from neighbouring regions may be used as a proxy. Moreover, the information can distinguish between multiple crops. Irrigation cost are estimated by taking irrigation equipment per household per crop per harvested area from LSMS-ISA and combine it with irrigation costs per ha per technology from literature to estimate irrigation costs per crop per ha per technology.

Since the region of interest (Mali, Niger, Nigeria) is dominated by small holder farms, using LSMS-ISA as the main source is a good estimator for the current status of required input variables. (Details on the LSMS_ISA database and crop list, usages and preparations are available upon request.).

Table 7: Variable names, description and unit in LSMS-ISA database

Variable name	Description	Unit
yield_per_hectare	Harvest volume (yield) per hectare	Kg/ha
p_crop_perkg	Crop prices	$/kg
family_labourdays_per ha, hiredlabour_days_per_ha	Labour days (family and hired) per hectare	Days/ha
water_source	Water source	
irrigation_method	Irrigation method (conveyance)	
irrigation_cost_per_ha	Irrigation cost per hectare	
input_cost_per_ha	Input cost (non-irrigation and non-fertiliser costs) per hectare	$/ha
N_kg_per_ha, P_kg_per_ha, K_kg_per_ha	N, P, and K fertiliser use per hectare	Kg/ha
N_cost_per_ha, P_cost_per_ha, K_cost_per_ha	N, P, and K fertiliser cost per hectare	$/ha

3.1.6.1. Harvest volume (yield)

Harvest data presents plot and crop level information on harvest volumes. For non-standard weight units, conversion tables are used (if available). Yields are determined by dividing the harvest volume by the cultivated area per crop per household.

Missing data per crop per technology per TSU were solved using corresponding more aggregated data per crop group, region and technology if necessary. Moreover, it should be acknowledged that yield data for most irrigated crops is very limited in the LSMS-ISA database. Therefore the uncertainty of the yield data especially for irrigated crops is large. To overcome this problem it is assumed that yield from irrigated crops is at least twice the yield of rainfed crops (see Table 8 and Table 9), in accordance with observed yield difference between rainfed and irrigated maize yield in LSMS-ISA data.

3.1.6.2. Crop prices

Crop prices can be approximated by dividing the sold revenue by the volume sold.

3.1.6.3. Labour input

The total amount of days worked by family labour and hired labour is extracted from the LSMS-ISA database. In some cases, pre-harvest and post-harvest labour days are indicated. If that is the case, the sum of days worked is taken for both family and hired labour.

Profits are calculated including hired labour costs. That is: Profit =Gross Output – Costs (including hired labour). LSMS-ISA data showed quite large differences in hired labour input costs per day per crop per technology per TSU. This was considered inconsistent. Therefore hired labour input costs per crop per technology per TSU per day was calculated as the minimum between minimum wages per day and the labour costs per crop per technology per TSU per day as reported by the LSMS-ISA database. This approach excludes extreme labour costs per day. Due to lack of data, minimum wage in Kenya was taken as indicator of minimum wage in model region[8].

To determine hired labour costs, the labour costs per day were multiplied by the amount of hired labour days per crop per technology per TSU per ha taken from LSMS-ISA database.

Missing data per crop per technology per TSU were again solved using corresponding more aggregated data per corresponding crop group, region and technology if necessary.

3.1.6.4. Irrigation use, cost, and area

Whether a given household uses irrigation is sometimes explicitly indicated. For Niger and Nigeria, the water source and/or the indicated method of irrigation (technology) is combined with information on irrigation costs per technology in Xie et al. (2014). Irrigation costs in Xie et al. (2014; table 6) include both operational costs and capital costs. The LSMS-ISA data for Mali already contains irrigation use and costs per crop per plot. This information has been combined with the size of the plot to calculate irrigation costs per crop per ha. To obtain more robust indicators, irrigation costs per crop are national (Niger, Nigeria, Mali) averages over all technologies and linked to the corresponding TSU's.

It was decided to exclude irrigation amount from the estimation of irrigation costs because LSMS-ISA has no information of irrigation amount in relation to irrigation costs and because the yield dataset, based on LSMS-ISA does not include a clear indicator for irrigation requirement.

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8 http://www.wageindicator.org/main/salary/minimum-wage/kenya

3.1.6.5. Fertiliser and other input costs

Fertiliser and other input costs per crop per technology per TSU are extracted and processed using the LSMS-ISA as the basic database in combination with some other sources such as Sheahan *et al*. (2014). A detailed description is given in ANNEX IV: LSMS-ISA crop list. First step was to create a link between the crops in the LSMS-ISA database and the 42 crops in the economic model.

The database provides plot level information on multiple types of fertiliser; commonly including urea, DAP, and NPK. These fertilisers are converted to N, P, and K concentrations using Appendix 2 in Sheahan et al. (2014). For example, a plot may indicate to be using 100 kg of DAP, which has a NPK rating of (18:46:0). Therefore, that plot is indicated to use 18 kg of N and 46 kg of P.

Similarly the costs of the original fertilisers are indicated. Sometimes the information is provided on the plot level, sometimes on the household level. In the latter case, the costs of fertiliser are assumed to be proportionally spread over the plots according to their share of the total area. The cost of these fertilisers are attributed to N, P, and K according to the proportion of the concentration. For the example above, the cost attributed to N would be 18 / (18 + 46) = 0.28125 and the cost attributed to P would be 46 / (18 + 46) = 0.71875. If the 100 kg dap cost $1,000 in total, $28,125 would be allocated to N, and $71,875 would be allocated to P.

Other inputs are considered non-irrigation and non-fertiliser costs including agricultural inputs such as seeds, pesticides, animals and machinery. This information is given on the plot-level or household level and was aggregated and attributed to a plot according to their size. Other costs related to agricultural activities may include (among others) fuel, electricity, taxes, and transport costs.

In a final step, plot resolution data are averaged to TSU. Missing data per crop per technology per TSU were solved using average costs per ha per corresponding aggregated crop group, region and technology if necessary.

3.1.6.6. Cultivated areas

The cultivated areas are indicated per crop based on household estimates.

3.1.6.7. Currency conversion and inflation

All monetary units are converted to U.S. dollars using the current exchange rate and scaling up to recent levels using inflation rates. The inflation rates are hailed from the World Bank[9] and the exchange rate is gathered from XE Currency Converter[10]. Final results are presented in EUR.

3.1.6.8. Attributing inputs and costs to crops

Inputs and costs are often indicated on the plot or household level. These inputs and costs were attributed to crops by using the revenue share of the crop in the total plot (or household) revenue. The equations that are used to calculate input amounts and costs per crop are specified in the guiding LSMS-ISA data document (ANNEX IV: LSMS-ISA crop list).

3.1.6.9. Spatial variables that affect costs

In general, the LSMS_ISA database provides data for plots or households and is averaged to obtain estimates per TSU. In case very few or no data are available for a TSU, information from neighbouring regions is used as a proxy. Co-variables were used to estimate spatial variation. Such as precipitation, soil type, distance to the nearest

9 . http://data.worldbank.org/indicator/FP.CPI.TOTL.ZG
10 . http://www.xe.com/currencyconverter/

(labour) market[11], elevation, slope, population density, infrastructure. This information was hailed from the LSMS-ISA database or obtained from open datasets, most of which are mentioned already in paragraph 3.1.2.

3.1.6.10. Average results of the LSMS-ISA database and total acreage rainfed and irrigated crops

Table 8 shows selected aggregated results for rainfed crops, while Table 9 shows selected aggregated results for irrigated crops. Results of individual MAPSPAM crops are aggregated to crop groups. Gross margin is calculated as yield times output price minus hired labour costs, fertiliser costs and other input costs. Irrigated gross margin exceeds the gross margin of rainfed crops for rice, leguminous crops, permanent oilseed crops, sugar crops and vegetables and melons. For the remaining crop groups' average gross margin of rainfed and irrigated technologies are similar; irrigated gross margin could be slightly above, but also slightly below rainfed gross margin. Hired labour costs seem high for rainfed permanent oilseed crops (see Table 8). It should be noted that LSMS-ISA data are based on the latest available year and limited to small scale producers. A long term average could give more reliable results and reveal structural differences in yield and cost data per crop per technology per region. The average production costs reported in Table 8 and Table 9 are much lower compared to Xie et al. (2014). The reason for this could be the use of different data sources and related unitary costs, prices and living standards. Xie et al. (2014) use household production costs data for Kenya. In this research we use LSMS-ISA data for Nigeria, Niger and Mali. In this research irrigation costs are among others also based on Xie et al (2014).

Table 8: Average hired labour costs, fertiliser costs, other input costs, yield, crop price, gross margin and total area per aggregated cropgroup. Rainfed area

	Hired labour	Ferti-lisers	Irri-gation[1]	Other inputs	yield	Output price	gross margin	Total area
	€/ha	€/ha	€/ha	€/ha	Kg/ha	€/kg	€/ha	1000 ha
Rice	24	27	0	19	716	0.41	259	2106
Cereals	13	19	0	21	542	0.29	125	21529
Fruit And Nuts	37	9	0	29	896	0.42	346	1234
Leguminous Crops	12	18	0	20	395	0.48	163	6924
Permanent Oilseed Crops	274	87	0	41	881	0.56	150	1179
Oilseed Crops	24	20	0	18	836	0.38	292	2451
Root Tuber Crops	32	18	0	23	1311	0.23	259	4622
Beverage And Spice Crops	6	6	0	71	631	1.24	795	778
Sugar Crops	43	31	0	24	860	0.47	354	16
Fiber Crops	20	40	0	35	671	0.46	249	1248
Veget. & Melons	69	24	0	60	1107	0.58	567	1186
Total								43952

[11] http://www.fao.org/docrep/003/x6998e/x6998e05.htm

1.operating costs and capital investments

Source: LSMS-ISA. Own calculations

Table 9: Average hired labour costs, fertiliser costs, irrigation costs, other input costs, yield, crop price, gross margin and total area per aggregated cropgroup. Irrigated area

	Hired labour	Ferti-lisers	Irri-gation[1]	Other inputs	yield	Output price	gross margin	Total area
	€/ha	€/ha	€/ha	€/ha	Kg/ha	€/kg	€/ha	1000 ha
Rice	44	69	161	28	1951	0.57	939	308
Cereals	26	36	260	63	1292	0.37	156	73
Fruit And Nuts	29	5	406	11	2428	0.26	258	2
Leguminous Crops	1	16	234	7	1138	1.17	1239	0
Permanent Oilseed Crops	22	55	291	79	1475	0.56	476	0
Oilseed Crops	22	55	291	79	956	0.60	192	3
Root Tuber Crops	0	5	234	27	2109	0.25	317	26
Sugar Crops	21	67	234	20	2395	0.57	1186	42
Fiber Crops	22	55	291	79	1472	0.34	110	11
Veget. & Melons	17	16	201	42	2583	0.66	1622	160
Total								656

[1]Irrigation costs include operating costs and capital costs. Irrigation costs per crop group are calculated as an area weighted average of irrigation costs per corresponding individual crop.

3.1.7. Estimated crop yield per TSU per technology per AS and CC

For the agricultural scenario runs, the yield estimates from LSMS-ISA (Table 8 and Table 9) are modified using ratios, derived from GAEZ yield levels.

$$\textit{Scenario-yield}_{sc} = \textit{LSMS-ISA-yield} * \textit{Ratio}_{sc}$$

Where:

sc = *BU-, HII-, MII- or EX-scenario*

The ratios are derived from various GAEZ input levels that reflect the different scenarios of this study (see also chapter 4). The crop model behind GAEZ v3.0 (IIASA/FAO, 2012) first calculates maximum attainable biomass and yield as determined by radiation and temperature regimes, followed by the computation of respective rainfed crop water balances and the establishment of optimum crop calendars for each of these conditions. Among other constraints, these calculations includes the following suitability screening:

thermal (latitudinal) climatic conditions, permafrost conditions, length of temperature growing period, length of frost free period, temperature sums, temperature profiles, vernalisation conditions and diurnal temperature ranges (IIASA/FAO, 2012).

For the BU and EX scenarios, the yields are directly based on LSMS-ISA (ratio = 1). For the HII and MII scenarios the ratios are calculated relative to the GAEZ low input level (for rainfed yield) or intermediate input level (for irrigated yield). See Table 10.

Thus, yields become specific per crop, per technology, per agricultural scenario and are aggregated to TSU resolution (*Yield*$_{i,j,r}$). For illustration purposes, resulting yields per aggregated crop group in scenario HII are given in Table 12.

Table 10: Ratios based on GAEZ potential yields, to derive scenario yield levels

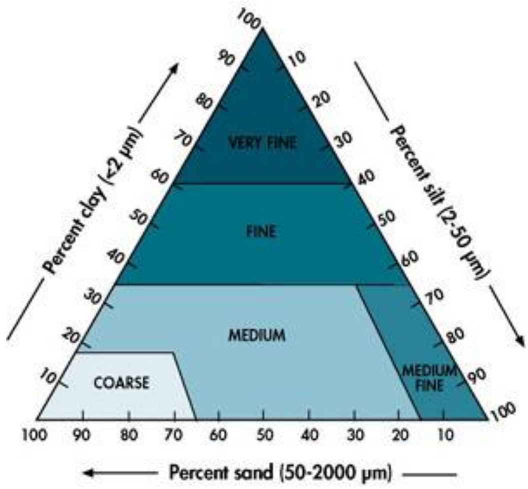
	Ratio
BU	1
	1
HII	GAEZ rainfed high input level / GAEZ rainfed low input level
	GAEZ gravity-irrigation high input level / GAEZ gravity-irrigation intermediate input level
MII	((GAEZ rainfed low input level + GAEZ rainfed high input level)/2) / GAEZ rainfed low input level
	((GAEZ gravity-irrigation intermediate input level + GAEZ gravity-irrigation high input level)/2) / GAEZ gravity-irrigation intermediate input level
EX	1
	1

3.1.8. Estimated nutrient and irrigation requirement per technology per AS and CC

3.1.8.1. Nutrient requirement

Nutrient requirements per scenario will be adjusted in a consistent manner with the yield changes per scenario. Nutrient requirement is represented by NPK and derived from organ specific dry matter fractions (*inter alia*, Nijhof 1987;Van Heemst 1988, Boons-Prins 1993). A base yield from the soil will be taken into account. Base yield is calculated by using soil texture properties from SoilGrids1km[12]. This yield is restricted to the nitrogen base supply per soil type which is maintained by the nitrogen fixation of the vegetation. This fixation is very low as under purely natural circumstances there is practically no nitrogen deposition resulting from intensive livestock systems and other sources. The base nitrogen supply is estimated per TSU based on its texture class (Figure 6). We assume that the N-base in the soil remains stable as there is a balance between nitrogen fixation and nitrogen removal by extensive grazing/harvesting. Without fertilisation techniques, soil fertility would quickly decrease under more intensive agricultural practices.

Figure 6: Base nitrogen levels per TSU in purely natural grassland conditions with extensive grazing by wild fauna (Source: European soil map texture classes, EU funded HYPRES database (HYdraulic PRoperties of European Soils), 1997)[13]



1 Coarse: 30kg/ha

2 Medium: 45kg/ha

3 Medium fine: 50kg/ha

4 Fine :40kg/ha

5 Very fine: 30kg/ha

Base nitrogen levels are first calculated per pixel per soil layer. In a second step the average base nitrogen levels per pixel is calculated, using the layer thickness (Table 11).

Table 11: Soil layer thickness

	Sd1	Sd2	Sd3	Sd4	Sd5	Sd6
Standard thickness (in meters)	0.05	0.1	0.15	0.3	0.4	1

This results in Figure 7, which are then aggregate from grid specific base nitrogen levels to TSU's.

[12] Hengl et al. 2014, SoilGrids1km — Global Soil Information Based on Automated Mapping.
(http://www.isric.org/content/soilgrids)

[13] https://www.hutton.ac.uk/learning/natural-resource-datasets/hypres/european-soil-map-texture-classes

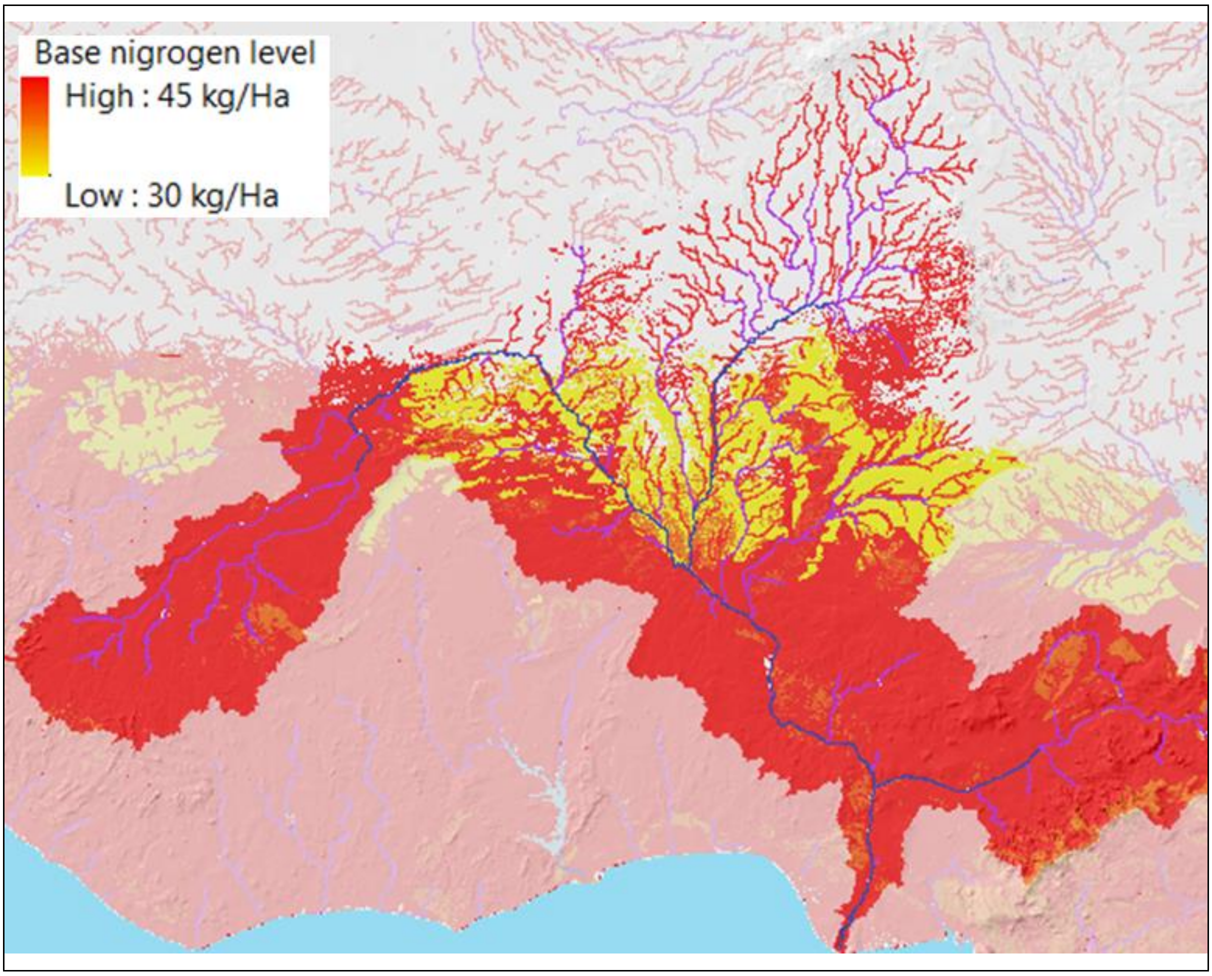


Figure 7: Base nitrogen levels per grid in purely natural grassland conditions with extensive grazing by wild fauna. Focus on Niger river basin. Background layers: Hillshade (GTOPO30) and major streams (HydroSheds).

The base nitrogen levels per TSU are used to estimate crop specific BASE_YIELD per TSU using crop specific N-fraction. BASE_YIELD is subtracted from GAEZ yields to derive NPK requirement per crop per TSU with a lower limit of 0. In a final step, NPK_YIELD is converted into N-, P,- and K-supply using organic specific dry matter NPK fractions and harvest index. Having both BU-NPK requirement and HII-NPK requirement based on GAEZ, these are then used as shifter for LSMS-ISA NKP requirements. Average fertiliser costs per aggregated crop group per technology in scenario HII are given in Table 13.

3.1.8.2. Irrigation requirement

To quantify water consumption under the different scenario's, irrigation requirement is estimated by means of the GAEZ Crop water deficit indicator: 'Suitability and Potential Yield', 'Climate yield constraints', 'Crop water deficit (mm)'. Irrigation requirement is estimated by multiplying irrigated crop areas (ha) with the crop water deficits (mm). The result is divided by 100.000 to express the outcome in 10^6 m^3.

Irrigation requirement per crop depends strongly on yield and is only calculated for the irrigated crops. Higher yields correspond to higher irrigation requirements. For each of the available crops, intermediate and high input level crop water deficit is downloaded for the 2050 Hadley CM3 A1F1 projection. The intermediate input level is used to estimate irrigation requirement for the BU and EX scenario. The high input level is used to estimate irrigation requirement for the HII scenario. Irrigation requirement for the MII scenario is estimated as the average between BU and HII.

3.1.9. Revenues for each TSU

Revenues per crop per technology per TSU per ha are calculated from the LSMS-ISA database. Missing data per individual crop are taken from corresponding averages of aggregated crop group, region and technology if necessary.

3.1.10. Partial equilibrium model for each TSU

The partial equilibrium model is based on Positive Mathematical Programming (PMP) (Helming, 2005; Howitt, 1995). As described above first a costs and revenue database was created for 42 crops, two technologies per crop and 201 TSU regions. Per crop per technology per TSU region the following costs components are included (euro per ha):

- N fertiliser
- K fertiliser
- P fertiliser
- Labour
- Irrigation
- Other input

Family labour data and suitability maps are used to define the quadratic PMP term.

3.1.10.1. Model specifications

The model assumes that producers are maximizing profits. The objective function of the model can be written as:

$$\boldsymbol{MAX\ Z = \Sigma_{i,j,r}\ Z_{i,j,r}} \qquad \textbf{(1)}$$

Where indices:

i represents crops *(1,...n)*

j represent technology *(1=non-irrigated, 2=irrigated)*

r represent regions (TSU's) *(1,...,n)*

Endogenous variable *Zi,j,r* is defined as

$Z_{i,j,r}$ *: Net revenue per crop i technology j per region r ($)*

The formula for $Z_{i,j,r}$ is written as:

$$\boldsymbol{Z_{i,j,r} = (Yield_{i,j,r} * Area_{i,j,r} * Price_{i,r}) - (Area_{i,j,r} * Costs_{i,j,r})} \qquad \textbf{(2)}$$

Exogenous variables or model input variables are:

$Yield_{i,j,r}$ *: yield per crop i per technology j per region r (kg per ha)*

$Price_{i,r}$ *: output price per crop i per region r ($ per kg)*

$Costs_{i,j,r}$ *: Including costs of hired labour, fertiliser, other inputs and irrigation per crop i per technology j per region r ($ per ha). Irrigation costs includes operating costs and capital costs*

To implement the concept of agricultural scenario's the above set of model input variables will be available in the 4 agricultural scenario versions.

The endogenous variable is:

$Area_{i,j,r}$: ha per crop i per technology j per region r

The first element of equation (2) gives the revenues. The second element gives the costs. The optimisation is subject to an area balance:

$$\boldsymbol{\Sigma_{i,j}\, Area_{i,j,r} \leq \Sigma_i\, TotArea_{i,r} \qquad [\pi_r]} \tag{3}$$

Where exogenous variable

$TotArea_{i,r}$: total area crop i in region r (ha)

π_r: shadow price for land in region r (\$ per ha)

The model is completed by the restriction that:

$$\boldsymbol{Area_{i,j,r} \geq 0} \tag{4}$$

3.1.10.2. Model calibration

The model presented above will not automatically replicate observed crop activity levels and technologies. Hence, a calibration method is needed. The model is calibrated to observed activity levels using Positive Mathematical Programming (PMP; Howitt, 1995).

The approach used in this research is as follows. First we determine the PMP term (Euro per ha per crop per technology per region). This term represents the non-linear part of the cost function. The PMP term is based on shadow family labour costs plus a risk term. Family labour costs per crop per technology per tsu per ha equals the above mentioned costs of hired labour per day times family labour days per crop per technology per tsu per ha. The latter is derived from LSMS-ISA data.

The risk term is equal to a risk aversion coefficient times the standard deviation of total costs. The risk aversion coefficient is valued between 1 and 2.5 (Elamin and Rogers, 1992). **The risk aversion coefficient per crop per technology per TSU is relatively large, close to 2.5, if the regional suitability of the crop is relatively limited.** Suitability is based on suitability maps per crop per technology per TSU (see paragraph 3.1.4). Due to high costs, the risk term of irrigated crops is large compared to rainfed crops.

$$\boldsymbol{PMP_{i,j,r}} = \text{FamilyLabourCost}_{i,j,r} + \rho_{i,j,r} * \sigma_{i,j,r}$$

Where PMPi,j,r is the PMP term (*\$ per ha),* Family Labour cost (*\$ per ha),* ρ is the risk aversion coefficient different per crop, technology and region depending on suitability of the crops and technologies, and σ is standard deviation of total costs. Due to a lack of enough empirical data this is assumed equal to 60% of the total costs.

Next, a constant term per crop per region per technology per ha (FACTi,j,r) was constructed to ensure that in the baseline marginal costs equals marginal revenue. In other words, this term explains the difference between marginal revenue and marginal costs in the initial situation, needed to calibrate the optimization model to observed crop activity levels.

$$\boldsymbol{FACT_{i,j,r} = (Yield_{i,j,r} * Price_{i,r}) - Costs_{i,j,r} - \pi_r - PMP_{i,j,r}} \qquad \textbf{(5)}$$

$FACT_{i,j,r}$: Constant term ($ per ha per crop per technology per region).

$PMP_{i,j,r}$: PMP term representing familie labour costs and risk aversion ($ per ha per crop per technology per region)

Shadow price of land is assumed equal to about 53 € per ha. However in regions with a share of cereals in total crop area of more than 50%, the shadow price of land is assumed about 36 € per ha. While in regions with high share of rice and/or sugar crops the land price is assumed equal to about 70 € per ha. The constant term FACT is included as a linear term in the objective function and kept constant in all scenarios.

The above assumptions concerning the average shadow price of agricultural land in the research region has been derived from different indicators and sources. Firstly, agricultural value added (in constant 2005 US$) was divided by agricultural area to compute value added per hectare to use as a proxy for total agricultural returns and shadow price of land. Data were taken from the FAO [14] and World Bank World Development Indicators (WDI) database.[15] This indicator shows large differences in land values, with land values in Nigeria exceeding the land values in Mali and Niger by far. Other indicators were taken from literature (Egbodion and Ahmadu, 2015; Kadiri et al., 2014). These authors report land values for rice production between 45 € per ha and 68 € per ha. The resulting average land values or shadow prices of land applied in this research, see above, are between the calculated figures and reported figures in the literature.

Besides regional differences, the irrigation/not irrigation factor should also be considered as an important driver of land prices. In fact, in many non-irrigated areas land market are extremely reduced/inexistent. Further research should also focus on the role of land markets. In case land renting prices exists in a given area, it could be used as shadow price of land. Until now this was not considered.

The PMP term is included as a quadratic cost function in the objective function. So the profit function (2) is rewritten as:

$$\boldsymbol{Z_{i,j,r} = (Yield_{i,j,r} * Area_{i,j,r} * Price_{i,r}) - (Area_{i,j,r} *(Costs_{i,j,r} + FACT_{i,j,r})) - PMP_{i,j,r}} \qquad \textbf{(6)}$$

And the PMP term[16], representing family labour cost and risk aversion is written as:

$$\boldsymbol{PMP_{i,j,r} = kk_{i,j,r} + \alpha_{i,j,r} Area_{i,j,r} + 0.5\, \beta_{i,j,r} (Area_{i,j,r})^2} \qquad \textbf{(7)}$$

[14] http://faostat.fao.org/

[15] http://databank.worldbank.org/data/reports.aspx?source=world-development-indicators

[16] The PMP term is written as a quadratic function of the area. The calibration of the parameters is based on the initial value of the PMP term given by the family labour costs and the risk coefficient in monetary units.

Where $kk_{i,j,r}$is the constant term and $\alpha_{i,j,r}$ and $\beta_{i,j,r}$ are parameter to be estimated. The non-linear PMP term in the total costs function of a certain crop and technology increases exponentially if the land allocated to that crop and technology increases. If the PMP term per crop per technology is large compared to total costs, the land allocated to the crop and technology combination will be rather sticky. This is especially the case for crops and technology increases in regions with low regional crop suitability. Also, high costs crops and technologies are considered rather sticky, see explanation above.

The first order derivative of the costs function of objective function (6), including the PMP term, will result into linear marginal costs functions. Assuming that all cross terms are zero, the linear marginal costs or inverse supply functions at the optimal activity level $Area^{*}_{i,j,r}$ can be written as

$$mc_{i,j,r} = Costs_{i,j,r} + FACT_{i,j,r} + \alpha_{i,j,r} + \beta_{i,j,r}\, Area^{*}_{i,j,r} \qquad (8)$$

Where:

$mc_{i,j,r}$: *marginal costs of activity i and technology j in region r ($ per ha)*

In this report exogenous supply elasticities are used as extra information to calculate parameters $\alpha_{i,j,r}$ and $\beta_{i,j,r}$ (Howitt, 1995; Helming, 2005).

Important driver of the models results is the long term supply elasticity per crop per technology per TSU. Data are collected from the literature. It was found that supply elasticity is relatively large for maize. A long term maize supply elasticity of 0.8 is assumed for all TSU. For crop groups cereals, leguminous crops and oilseed crops the supply elasticity is halve the supply elasticity for maize. For all other crop groups the supply elasticity is assumed 15% of the maize supply elasticity.

3.1.11. Select most profitable AS per TSU

Rather than applying each agricultural scenario as a blanket approach over the entire river basin, this step starts with selecting the most profitable scenario per TSU. It is considered as a post processing step.

As a first step, 'most profitable AS' is defined using the net revenue as profitability score, but other estimators are conceivable. In the second step this profitability score is calculated per TSU per AS (or already available as in the case of net revenue). Finally for each TSU, the AS with the highest profitability is selected. This still assumes applying a blanket approach of an AS within the TSU, but the most profitable AS can be different between TSU's. This is called the inter-TSU-mixed scenario.

Alternatively in the second step for each TSU a weighted average of the four AS's output results is calculated where the profitability elements are used as a weight. This can be interpreted as an intra-TSU-mixed-scenario (multiple scenario's within each TSU).

3.1.12. Aggregate results to AEZ and country resolution

In this post processing step model output results are aggregated to Agro Ecological Zone (AEZ) and administrative regions using the Global Environmental Stratification (GEnS)[17] zonation.

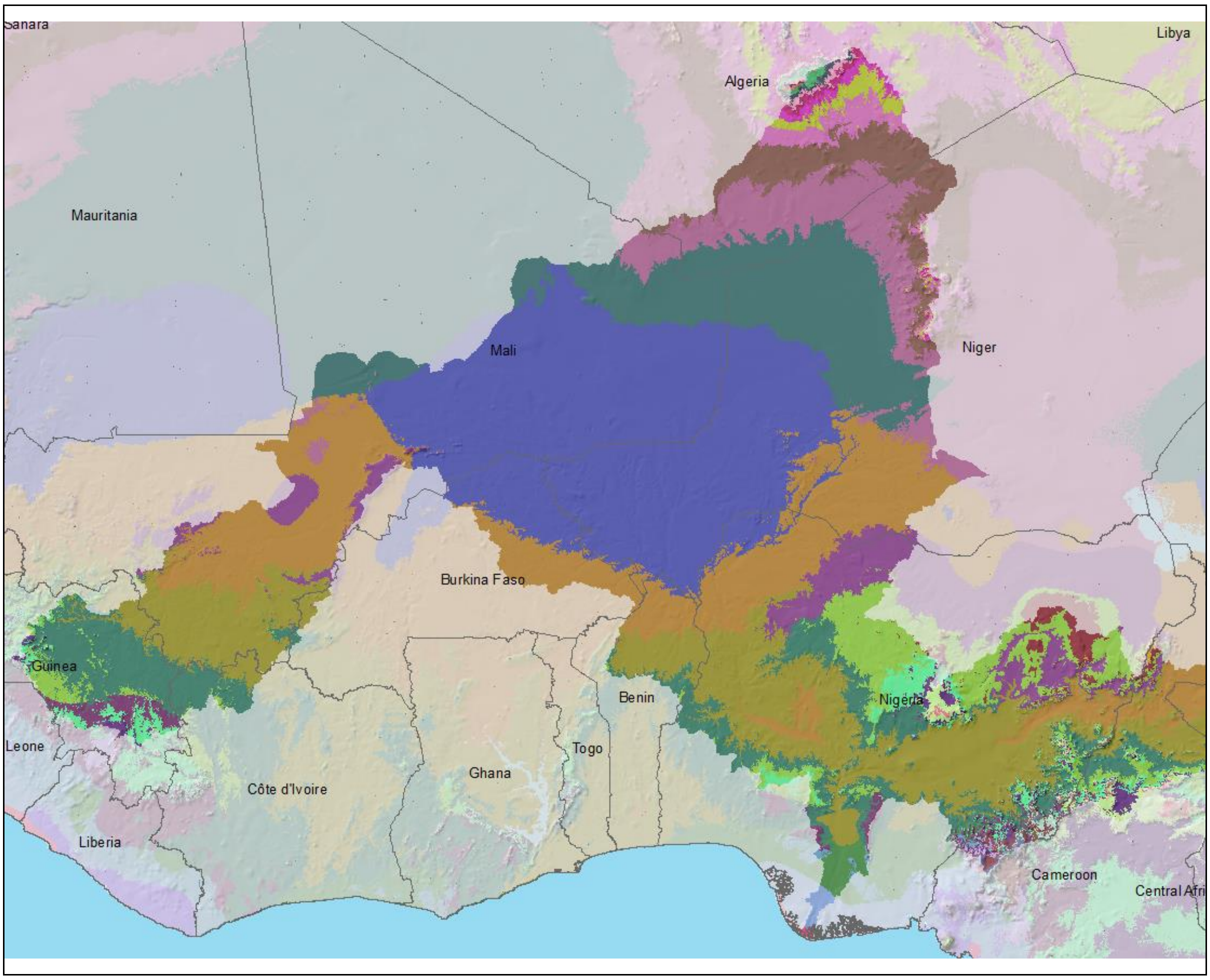


Figure 8: GEnS in the Niger River Basin. Source: GEnS Metzger 2012, Countries: GADM 2.8, Hillshade: GTOPO30.

In addition there will be an intersection with administrative regions. For instance to link input data that is available for administrative regions and to aggregated final results to administrative resolution. Global Administrative Areas (GADM 2.8 (November 2015)[18] is used as dataset.

The scenarios (AS-CC combinations) are compared/summarised per country and AEZ in tables and or graphs.

4. Scenario modelling

Scenarios are defined, with reference to a baseline situation, to support the scenario modelling. They are similar to scenario's as described in Ceccarelli *et al.*, 2016 where

[17] Marc J. Metzger, Robert G. H. Bunce, Rob H. G. Jongman, Roger Sayre, Antonio Trabucco and Robert Zomer, 2013. A high-resolution bioclimate map of the world: a unifying framework for global biodiversity research and monitoring. Global Ecology and Biogeography
Volume 22, Issue 5, pages 630–638.

[18] http://www.gadm.org/

each scenario is described as function of a socioeconomic context, a productive context specifically addressing the agricultural sector and a climate context. However, due to missing data, time and budget limitations, quite some simplifications have been applied. Each of the 4 scenario's is described by elements to be used in the modelling, namely: Area expansion, yields, NPK fertiliser, labour, irrigation and other costs.

Area expansion

Within the physical area of each TSU, potentially it is possible to increase production by expanding crop area. In the BU and HII scenario this is initially not allowed. In the EX scenario, area expansion is allowed as the single option to increase production. In the MII scenario the allowed expansion is half the size if the EX scenario. To assess the impact of area expansion in the HII scenario this is included in the sensitivity analyses.

Yields

In the case of BU and EX the yield levels are considered as they are, i.e. as in LSMS-ISA (see paragraph 3.1.6.1, Table 8, Table 9 and Table 10). HII represent the scenario where production increase is caused by increasing yields. Yields are higher because of increased input. MII again represents an in-between scenario.

NPK fertiliser

NPK requirement is directly derived from yield levels and therefore proportional to the yields.

Labour, Irrigation and other costs

Costs are considered independent from attainable yield or scenario and therefore not mentioned under the scenarios below. Cost per hectare per crop per technology per TSU are presented in Table 8 and Table 9 and are considered constant towards 2050 for all scenarios. The effect of a 50% decrease of irrigation costs (operating costs and capital investments) in the HII scenario is assessed in the sensitivity analyses. This could be considered as a governmental intervention to stimulate irrigation. In the same way, the effect of a 20% increase in output price is tested in the sensitivity analyses. A third way of assessing cost sensitivity is to consider a 50% decrease of total marginal costs related to risk and family labour input which reflecting a long term efficiency gain towards 2050.

4.1. Business as usual (BU)

This is the baseline scenario and will be used as the reference for relative quantitative comparison with other scenario's. The underlying assumption is a present state and trend in terms of the elements.

As said, due to missing data and resource limitations, autonomous developments concerning development of area per crop per technology per TSU and costs and revenues per crop per technology per TSU could not be quantified. Instead it has been assumed that base year values also apply to the 2050 BU scenario. More specifically, the BU scenario starts from the economic and technical variables for rainfed and irrigated crops as presented in tables 14 and 15.

Total harvested area per TSU under the BU scenario is equal to total harvested are per TSU of the MAPSPAM dataset reflecting the 2004-2006 situation, see Table 8 and Table 9. It means that for the BU scenario no area expansion is considered and it reflects the 2004-2006 harvested area situation.

Yields in scenario BU are presented in Table 8 and Table 9. These are directly based on LSMS-ISA data.

Average fertiliser costs per crop group in scenario BU are presented in Table 8 and Table 9. Fertiliser costs will be lowest in the BU scenario since they are proportional to the estimated attainable yields. Unit costs towards 2050 are assumed constant.

4.2. Medium Input Intensification (MII)

In the Medium Input Intensification scenario, is an intermediate scenario which could be associated several intensification paths, the underlying assumption is the adoption of medium performing agricultural technologies.

The main difference will be that the input levels will be increased beyond the BU level and a limited area expansion (max 5%) is allowed. However: yield levels are smaller than the HII scenario and area expansion is smaller than the EX scenario.

Expansion of cultivated land outlined in the MII scenario takes place beyond the BU trend but below the EX scenario where production increase is to be obtained by area expansion only. Total harvested area per TSU under the MII scenario is equal to total harvested area per TSU of the MAPSPAM dataset reflecting the 2004-2006 state plus a maximum allowed increase of 5%. Depending on the local situation (crops, technologies, prices, costs, etc.) the maximum expansion may or may not be reached.

Irrigated and rainfed yield levels are based on LSMS-ISA, applying a ratio's based on GAEZ yields to increase the yield (see paragraph 3.1.7). GAEZ datasets used:

- rainfed low input level yield
- rainfed high input level yield
- gravity-irrigation intermediate input
- gravity-irrigation high input
- Time: future period 2050s
- Scenario: Hadley CM3 A1FI
- CO2 Fertilisation: without co2 fertilisation

Costs will be intermediate in the MII scenario since they are proportional to the estimated attainable yields. Unit costs towards 2050 are constant.

4.3. High Input intensification (HII)

Here the underlying assumption is the adoption of agricultural technologies for crop production intensification with an emphasis on "Green revolution" solutions and agricultural yields in a narrow perspective, i.e.: high-yielding cultivars (implying improved seeds), synthetic fertilisers, irrigation, and (conventional) pest and weed control, with higher application intensities than for MII. This is developed regardless of environmental concerns (e.g. pollution, salinity level increases in groundwater) and potential negative effects on wild biomass production.

Total harvested area per TSU under the HII scenario is equal to total harvested are per TSU of the MAPSPAM dataset reflecting the 2004-2006 situation; similar as the BU scenario. It means that for the HII scenario no area expansion is considered and it reflects the 2004-2006 harvested area situation.

Yields of scenario BU are multiplied with the ratio between high input yields from GAEZ and low input yields from GAEZ (see Table 8, Table 9 and Table 10).

Irrigated and rainfed yield levels are based on LSMS-ISA, applying ratio's based on GAEZ yields to increase the yield (see paragraph 3.1.7). GAEZ datasets used:

- rainfed high input level yield
- rainfed low input level yield
- gravity-irrigation high input level yield
- gravity-irrigation intermediate input level yield
- Time: future period 2050s
- Scenario: Hadley CM3 A1FI
- CO2 Fertilisation: without co2 fertilisation

Costs are highest in the HII scenario since they are proportional to the estimated attainable yields. Unit costs towards 2050 are constant.

4.4. Extensification (EX)

Production growth in this scenario is mainly based on the expansion of the agricultural frontier. Input levels and resulting yields are equal to the BU scenario.

In this scenario production growth is based on the expansion of cultivated land. In principle, the maximum allowed expansion is twice as high as for the MII. Total harvested area per TSU under the EX scenario is equal to total harvested are per TSU of the MAPSPAM dataset reflecting the 2004-2006 situation plus a maximum allowed increase of 10%. Depending on the local situation (crops, technologies, prices, costs etc..) the maximum expansion may or may not be reached.

Yields are assumed equal to the yield in scenario BU. Costs are assumed equal to the fertiliser costs in scenario BU. Total fertiliser costs per TSU will be higher compared to the BU scenario in case area expansion is realised although unit costs (per hectare) are kept constant towards 2050.

5. Analysis and Results

5.1. Costs and revenues

Table 8 and Table 9 present average aggregated costs and revenues per crop group for rainfed and irrigated crops in the reference scenario BU.

5.2. Yields

Table 12 shows the average yield per aggregated crop group in BU and HII scenario over all TSU's. Scenario HII shows that in relative terms the increase in rainfed yield exceeds the increase in irrigated yield by far. An exception is the average yield increase in irrigated fruit and nuts.

Table 12: Average yield per cropgroup and technology in BU and HII scenario (kg per ha)

	Rainfed		Irrigated		Percentage difference	
	BU	HII	BU	HII	rainfed	irrigated
Rice	803	2549	2188	5417	218	113
Cereals	608	2414	1450	5125	297	112
Fruit And Nuts	1005	3538	2724	12517	252	254
Leguminous Crops	443	1362	1277	3316	207	144
Permanent Oilseed Crops	989	3254	1655	7157	229	120
Oilseed Crops	938	3622	1072	5497	286	52
Root Tuber Crops	1471	5139	2366	9648	249	88
Sugar Crops	965	3808	2686	10638	295	179
Fiber Crops	752	3009	1652	4546	300	51
Veget. & Melons	1242	4208	2897	9905	239	135

5.3. Fertiliser costs

Table 13 shows average fertiliser costs per crop group and technology in the BU and HII scenario. Fertiliser costs increases both for rainfed and irrigated crops in HII scenario as compared to BU. However, the impact can be quite different per crop group and technology. Especially for irrigated Fruit and Nuts, Leguminous crops and Root and Tuber crops the increase in fertiliser costs is very large, although it increases from a very low base.

Table 13: Average fertiliser costs per cropgroup and technology in BU and HII scenario (euro per ha)

	Rainfed		Irrigated		Percentage difference	
	BU	HII	BU	HII	rainfed	irrigated
Rice	27	61	69	126	124	82
Cereals	19	181	36	133	866	270
FruitAndNuts	9	10	5	51	10	867
LeguminousCrops	18	111	16	411	511	2530
PermanentOilseedCrops	87	90	55	292	4	428
OilseedCrops	20	103	55	128	405	132
RootTuberCrops	18	77	5	399	330	7291
SugarCrops	31	123	67	391	295	481
FiberCrops	40	54	55	58	35	5
Veget. & Melons	24	87	16	43	258	169

5.4. Acreage and shares

The baseline situation of acreages was retrieved from MAPSPAM (see 3.1.5). The total crop area (rainfed + irrigated) in this baseline situation is shown in Figure 9. Irrigation share in the baseline situation is show in Figure 10.

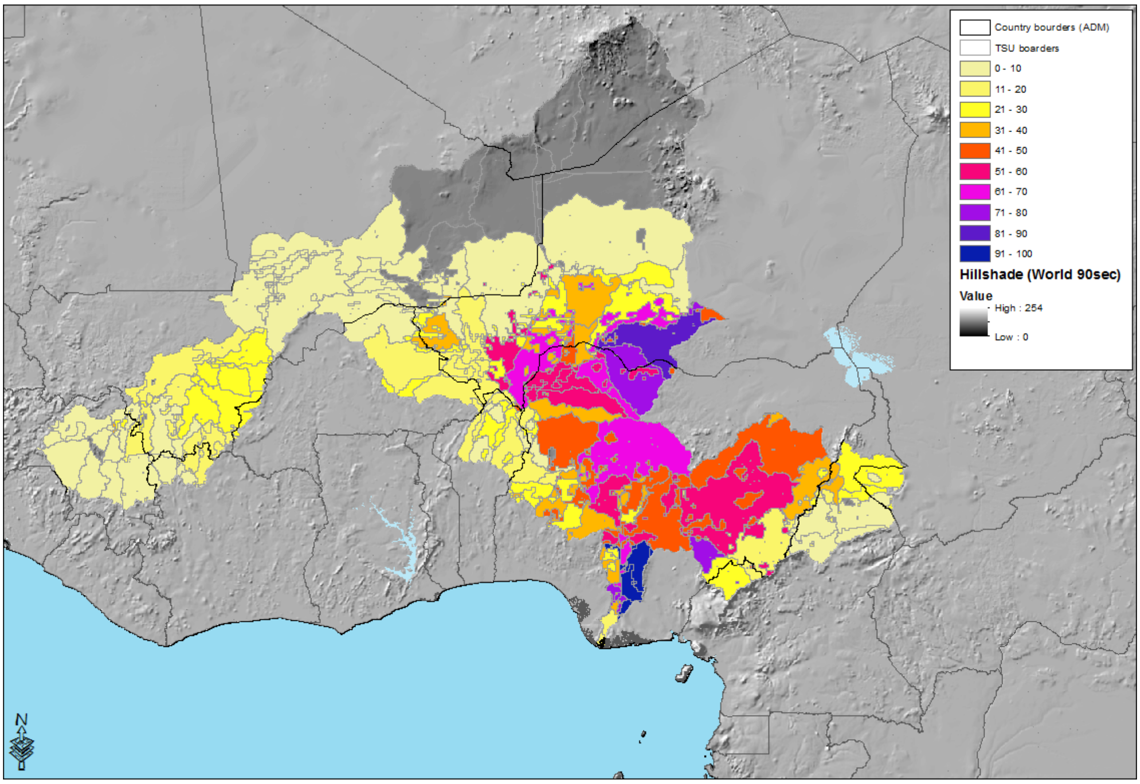


Figure 9: Mapspam total rainfed + total irrigated area as fraction of total physical area per TSU.

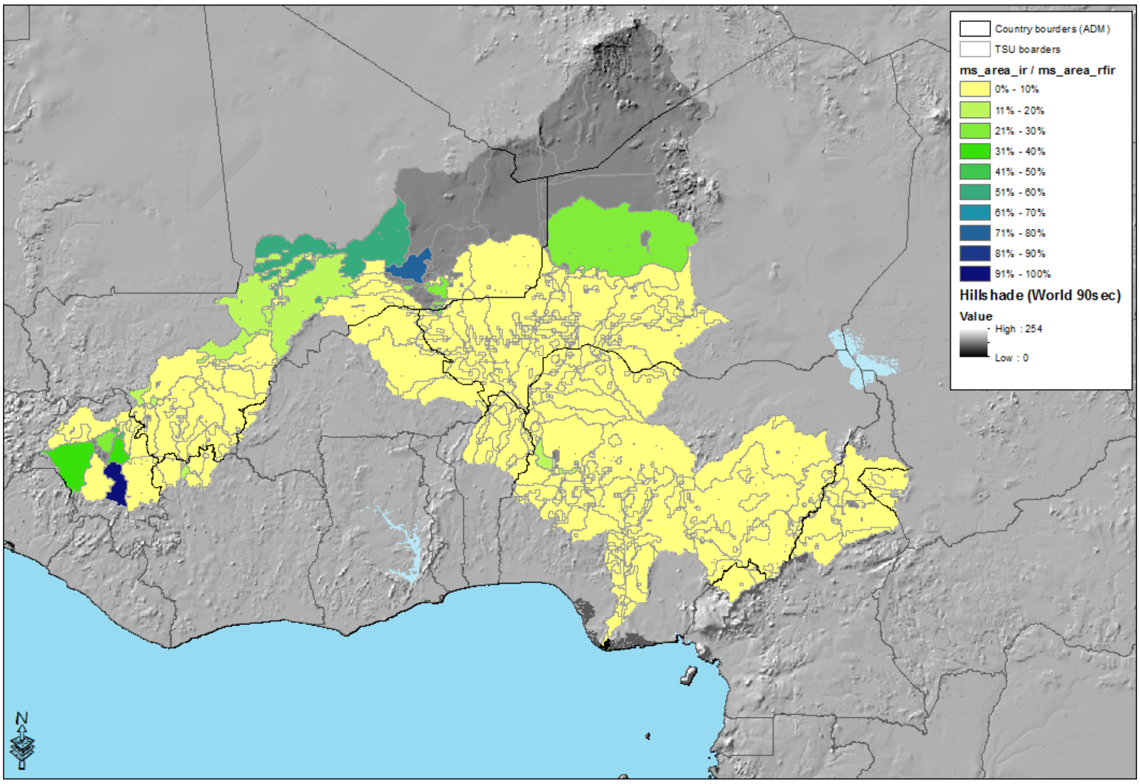


Figure 10: Mapspam irrigation share as fraction of total crop area per TSU.

Irrigation shares as fraction of total crop area per TSU show little difference between the different agricultural scenario's when displayed on a map (see ANNEX VI Irrigation share per TSU under different scenarios.) because the data range is large and differences are relative small. Normalised differences (normalised by BU) reveal the differences more clearly (Figure 11):

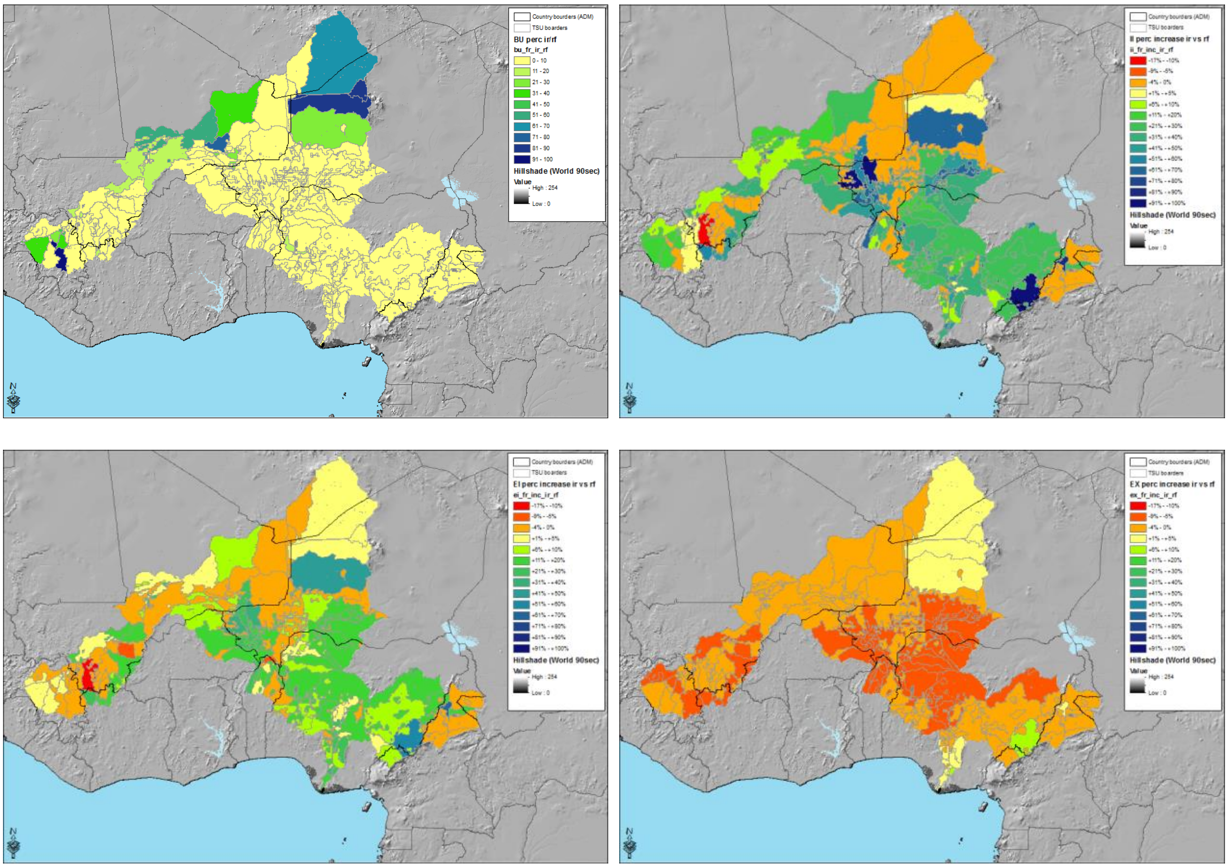


Figure 11: BU irrigation share as fraction of total crop area per TSU (top left). Percentage increase compared to BU: HII (top right), MII (bottom left), EX (bottom right).

Table 14 shows that in scenario BU about half of the crop area consists of cereals. About 75% of the total crop area consists of cereals, leguminous crops and root tuber crops. Table 15 shows the irrigated area per aggregated crop group in scenario BU. Rice and Vegetables and Melons account for about 72% of the total irrigated area in the Niger delta region. Share of irrigated area in total area is about 1.47%. Table 14 and Table 15 also show the normalised differences of acreage and irrigation share with between the BU and scenario's HII, MII and EX.

BU versus HII

There is a slight tendency to decrease the share of cereals and legumes in total cropping area in scenario HII, in favour of especially oil seed crops, sugar crops, fiber crops and vegetables and lemon. The acreage of irrigated crops increased in the HII scenario, compared to BU for all crops except legumes. As a result the share of irrigated area in total cropping area increased from 1.47% in BU scenario to 1.79% in scenario HII. This is also clearly visible in the top right map of Figure 11. In Nigerian part of the Niger delta, Irrigation seems favourable for the complete Niger delta in Nigeria. In Niger and Mali, some areas seem to be less favourable for irrigation (orange and red in top right map of Figure 11.

BU versus MII

In MII scenario total crop acreage in all regions increased with maximum of 5%. Yield and fertiliser costs changes per crop per technology are halve the changes of scenario HII. Table 14 shows that acreage of all crops increased and there is a slight tendency to increase the share of irrigated crops in total crop acreage in MII scenario as well, see Table 15. Impact on leguminous crops both in HII and MII scenario is lagging behind due to relative limited yield increase and relative high fertiliser costs increase. The relative increase of total irrigation share is still clear in Niger and Nigeria. In Mali, normalised differences are more often only slightly increasing or decreasing (0% +/- 5%), see lower left map of Figure 11.

BU versus EX

In scenario EX - with more crop land available and yield and fertiliser costs unchanged compared to the BU scenario - acreage of both rainfed and irrigated crops increased. In this scenario there is a slight tendency to increase the share of rainfed cereals in total cropping plan, as this is the activity that can be increased against lowest marginal costs in the model. This is why the total irrigation share slightly decrease in EX compared to BU. This is also reflected by the lower right map of Figure 11 where almost the entire Niger Delta shows decreasing numbers (light and orange).

In general, irrigated area is quite sticky in the model among others because of high costs and high risks associated with increased irrigation. This explains the relative limited increase in irrigated area in scenario EX, but also in scenario HII and MII. The data and elasticities in our model are such that acreage of irrigated area is indeed rather inelastic. This needs further research, but seems supported by literature such as You et al. (2010), who find that it is unlikely that more than 1% to 10% percent of the irrigation potential identified can be implemented over the next 20 years. This is especially due to the investment costs

Table 14: Total acreage per crop group (ha) and share in total acreage per crop group (percentage) in BU scenario. Acreage per crop group in HII, MII and EX (index, BU =100)

Cropgroup	BU	Share	HII	MII	EX
	ha	%	Index (BU=100)		
Rice	2.414.501	5	100	103	104
Cereals	21.602.385	48	97	107	112
FruitAndNuts	1.236.307	3	100	102	102
LeguminousCrops	6.924.102	16	93	95	110
PermanentOilseedCrops	1.179.321	3	101	101	100
OilseedCrops	2.454.211	6	125	123	110
RootTuberCrops	4.647.511	10	101	103	103
BeverageAndSpiceCrops	777.945	2	100	100	100
SugarCrops	57.909	0	138	120	102
FiberCrops	1.259.393	3	116	112	105
Veget. & Melons	1.346.582	3	111	107	102
Othercrops	708.363	2	100	100	100
Total	44.608.529	100	100	105	109

Table 15: Irrigated acreage per crop group (ha) and share in irrigated acreage per crop group (percentage) in BU scenario. Acreage per crop group in HII, MII and EX (index, BU =100). Share irrigated area in total area per scenario (percentage)

Cropgroup	BU	Share	HII	MII	EX
	ha	%	Index (BU=100)		
Rice	308.285	47.0	113	107	101
Cereals	72.971	11.1	144	140	112
FruitAndNuts	2.362	0.4	161	133	103
LeguminousCrops	56	0.0	91	98	103
PermanentOilseedCrops	195	0.0	141	122	102
OilseedCrops	3.165	0.5	195	182	107
RootTuberCrops	25.651	3.9	113	106	102
SugarCrops	41.916	6.4	147	125	101
FiberCrops	11.177	1.7	106	104	101
Veget. & Melons	160.388	24.4	124	114	102
othercrops	30.152	4.6	100	100	100
Total	656.319	100.0	121	114	102
share in total area	1.47%		1.79%	1.59%	1.39%

From the above irrigation shares, irrigation requirement is derived by multiplying irrigated crop areas with the crop water deficits (see 3.1.8.2). Irrigation requirements increase under the HII and MII scenario (see table Table 16) indicating increased demand for irrigation water. The impact is however rather limited as a) irrigation is expensive and b) increase in irrigation area is dampened in regions with large potential to increase yield of rainfed crops. Under HII and MII, the yield increase of rainfed crops is relatively large.

In this study, water requirement was not in a direct way verified against water availability. Primarily because water availability is difficult to integrate without an underlying hydrological model (i.e. in a limited study such as this). Instead, a post modeling comparison was executed between the irrigation requirement and water availability. It must be said that such comparison should be treated with caution because data come from different sources, have different model components and scenario assumptions. Potentially these factors all contribute to differing outcomes.

Two data sources seemed available to sideways compare irrigation requirement with water availability: The UNH-GRDC Composite Runoff Fields V1.0 (Balázs et al., 2000) and Niger-Hype from SMHI (Andersson et al., 2014). Although the former dataset is much older, it has the advantage to be open source. The later dataset is the results of a much more recent study but raw data are not freely available. A rough comparison was made between both sets by geo-referencing a screen dump of the Niger-Hype long term average total runoff from land, classifying and aggregating it towards TSU's. The Composite Runoff Fields data were directly aggregated toward TSU's (left side Figure

12). Differences between both datasets were calculated and proved relative low: in arid areas, differences are always < 25 mm/yr (right side Figure 12).

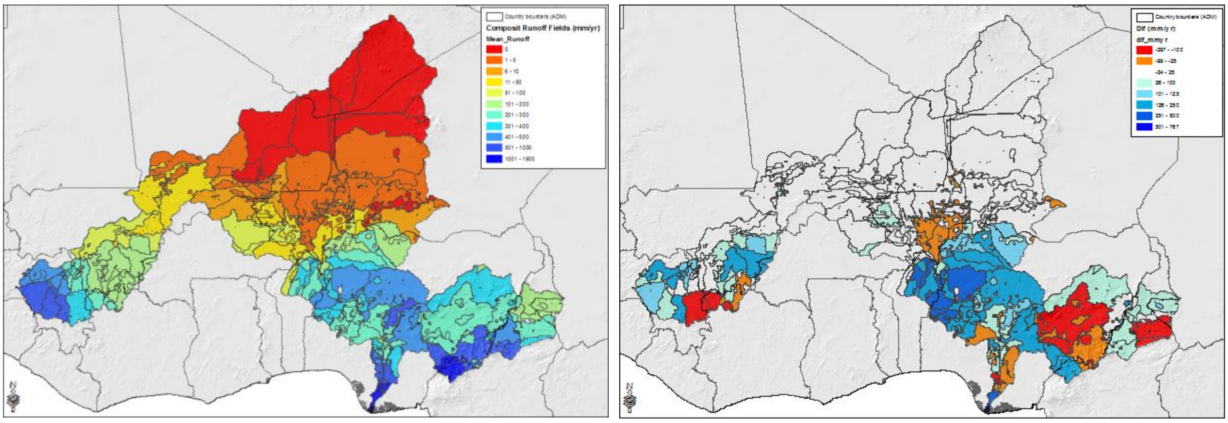


Figure 12: Left: Composite Runoff Fields V1.0 (Balázs et al., 2000) in mm/yr for each TSU. Right: rough differences between Composite Runoff Field and Niger-Hype (Andersson et al., 2014) in mm/yr for each TSU.

Because differences are relative small, we continue with the available Composite Runoff Fields (CRF) dataset. CRF is converted to m^3 using Mapspam total rainfed + total irrigated area, assuming runoff is only locally available in crop areas (i.e. not transported to crop areas). The water exploitation index (WEI) is used to account for maintaining long-term average availability of the freshwater water resources within a river (sub)basin. WEI is defined as the total water withdrawals-to-water availability ratio within a river basin. Withdrawals < 20% are causing a low water stress. To estimate water availability under expansion scenario's such the EX-scenario (max 10% expansion), CRF is also converted to m^3 assuming a 10% area increase in each TSU, as follows:

*Available Water = CRF * crop area * expansion * WEI*

Where:

WEI = 0.2

Expansion = 1 (no expansion) or 1.1 (10% area expansion)

In Figure 13 on the left, BU irrigation requirement is subtracted from available water without expansion. On the right, HII irrigation requirement is subtracted from available water, taking into account the 10% crop area increase. According to this comparison, some major TSU's in Mali have a negative balance that becomes more negative under an expansion scenario. In the more norther regions of Mali and Niger, the balance is more neutral with low requirements and low availability. TSU in Nigeria have a positive balance. Again, these conclusions should be interpreted with caution. A more integrated model is needed to link requirement and availability.

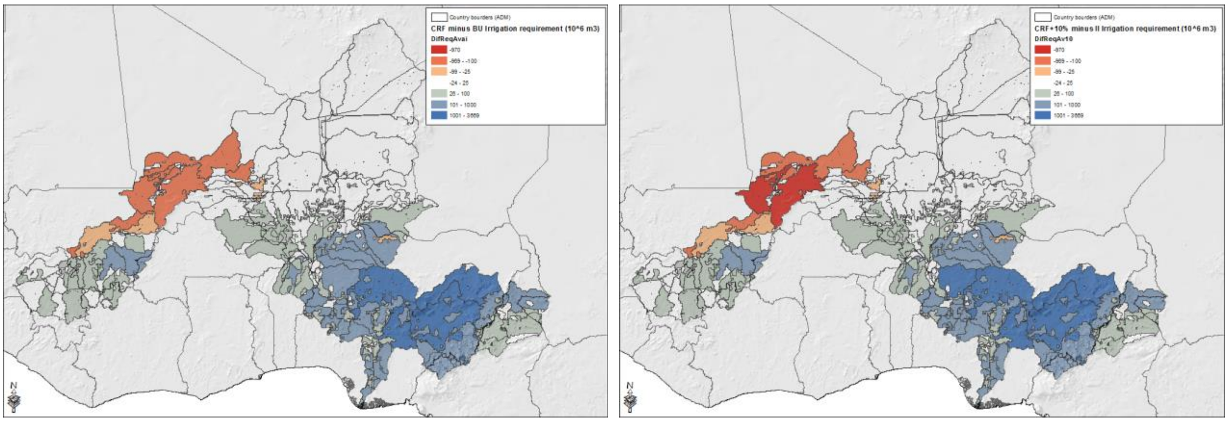


Figure 13: Left: CRF minus BU irrigation requirement. Right: CRF taking into account 10% area increase minus HII irrigation requirement.

Another source of available water could come from groundwater. Crucial groundwater availability datasets are not freely and readily available, available datasets require additional processing before estimates can be presented (e.g. account for contradictory climate change affects). Similar to the above available water comparison a comparison with other studies is difficult, if not impossible within the framework of this study. The different studies cover different regions, include different irrigation technologies, use different data sources, have different model components and scenario assumptions. Potentially these factors all contribute to differing outcomes.

Having said this, and without trying to explain the differences, Pavelic (2013) estimates that there are considerable amounts of available ground water that could be used for irrigation, even in arid and semi-arid countries such as Niger and Mali. Pavelic concludes that Mali (8.7%-216%) and Nigeria (6.3%-166%) have a moderate irrigation potential where % is relative to non-irrigated arable land. Niger has a low irrigation potential (0,1%-7,3%). On the other hand they conclude that no country has sufficient recharge levels to apply high input irrigation on all arable land. For Mali, Niger and Nigeria together they estimate a potential increase of high input irrigated area between 4.9 - 2.15 mio ha. Altchenko et al. (2015) estimate the (groundwater) irrigable area for Mali, Niger and Nigeria between 2.9 and 7.1 mio ha. Relative to the total cultivated land (from FAO AQUASTAT), this is between 4.5% and 11.0%. Xie et al (2014) estimate a total irrigation potential expansion of 21 mio ha when fully rolling out their four investigated irrigation technologies (motor pumps, treadle pups, small reservoirs and communal river diversion) over Mali, Niger and Nigeria. Relative to the total cultivated land (from FAO AQUASTAT), this is around 32.5%.

These figures are much higher than results from our study where we find total irrigated areas of 656.319 ha for the BU scenario to 794.145 for HII scenario (index 121). Stimulating irrigation as was done in the sensitivity analyses (paragraph 5.7) increases the total irrigated area to 971.352 ha. Again, the comparison should be treated with care. Our study areas cover the Niger river basin, mainly - but not entirely - including Mali, Niger and Nigeria and not excluding other countries in the delta. Also other differences mentioned earlier make the comparison difficult. In our case, the BU scenario is based on observed yield data, where water requirement is apparently met. From this we conclude that the increased water requirements for the EX scenario (+2%), HII (+26%) and MII (+15%) scenario should be easily met by ground water irrigation potential.

Table 16: Irrigation requirement from crop production under different scenarios.

	BU	HII	MII	EX
		Index (BU = 100)		
Irrigation requirement (mio m3 per year)	3280	126	115	102

Mapping absolute irrigation requirements for the different scenarios side by side show little difference (see ANNEX VII: Irrigation requirement in 10^6 m^3 per TSU under different agricultural scenarios.) because the data range is large and differences are relative small. Normalised differences (normalised by BU) reveal the differences more clearly:

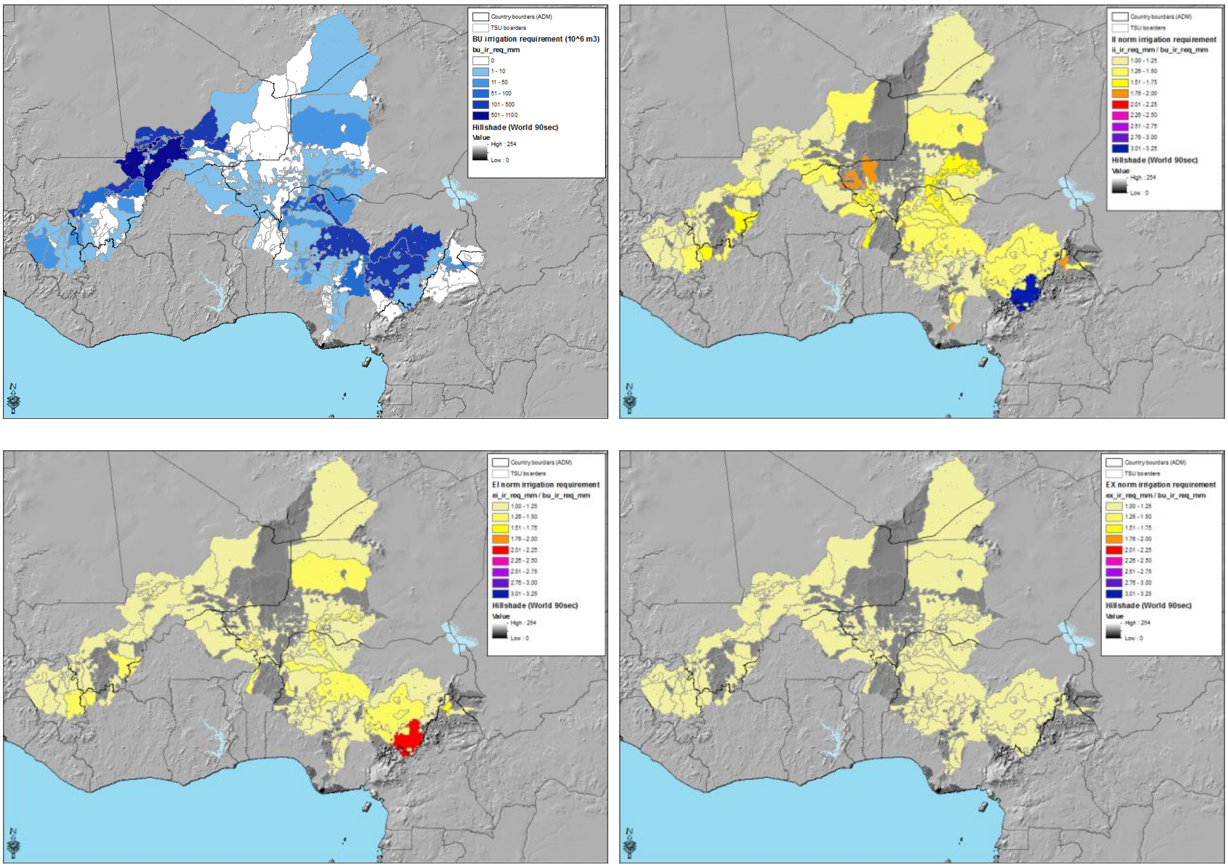


Figure 14: BU irrigation requirement in 10^6 m^3 per TSU (top left). Normalised irrigation requirement: HII by BU (top right), MII by BU (bottom left), EX by BU (bottom right).

Xie et al. (2014) estimate for their baseline scenario in Mali, Niger and Nigeria a combined irrigation requirement of 36 billion m3 per year which they estimate as a small fraction of SSA annual renewable water resources. This is much higher than the irrigation requirement estimated in our study and raises questions that need further investigation. The difference can partly be explained by the large difference in irrigation expansion, different methods to estimate irrigation requirement and regional extents.

In Figure 14 we see that relative irrigation requirements (relative to the BU scenario) increases in the HII, MII and EX scenario's for all regions. In some regions the irrigation requirement doubles or triples, especially in the HII scenario but only where the absolute requirement is low (1-10 mio m^3). When comparing above maps to long term average annual precipitation (Figure 15) most of the increase is realised in areas with precipitation levels greater than 250 mm per year, except for the northernmost TSU's. Even there, limited groundwater irrigation potential is present according to Pavelic (2013).

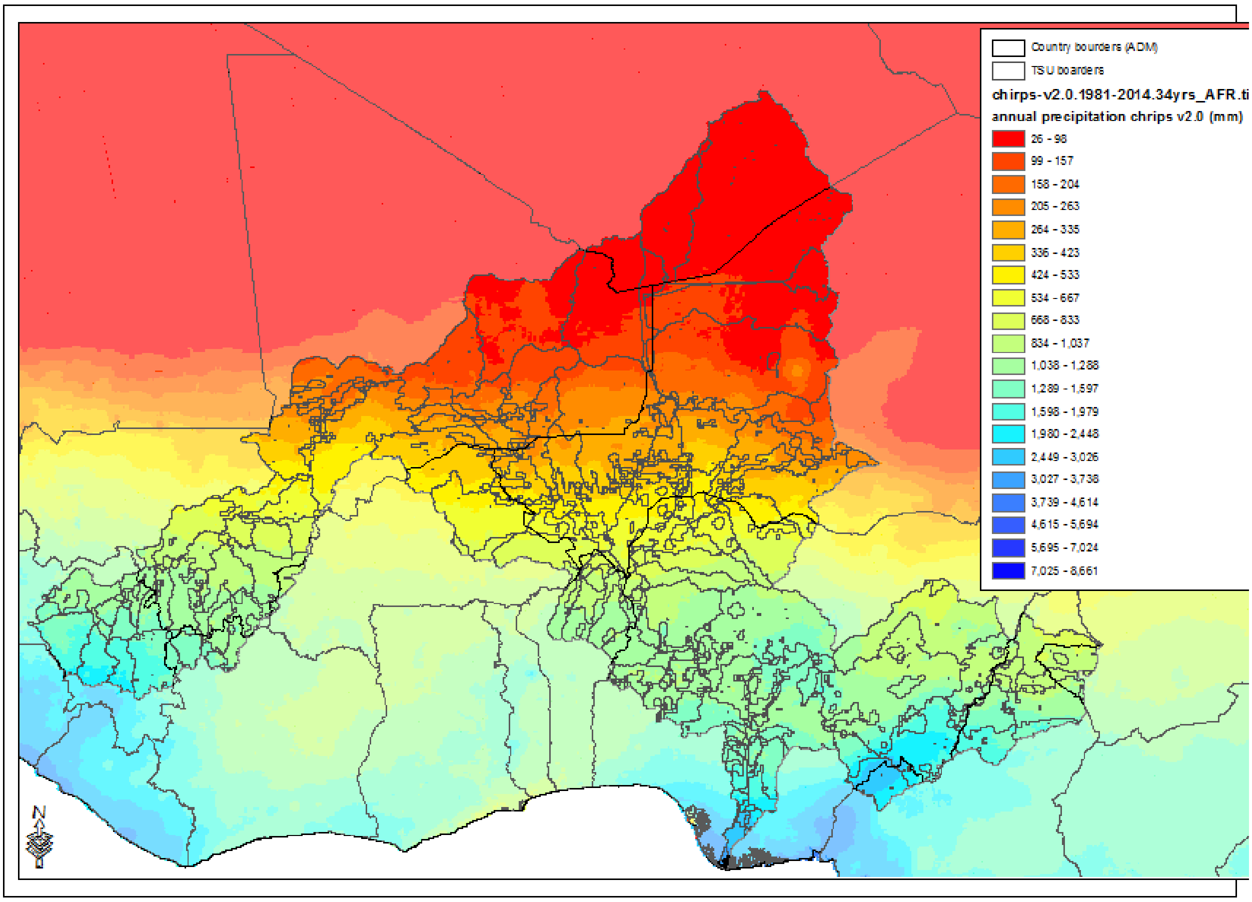


Figure 15: Long term average rainfall according chirpsv2.0 (1981-2014) in relation to TSU's

5.5. Profitability (revenue minus costs)

Table 17 shows some selected results from the scenarios in the total rainfed plus irrigated area. Clearly profits increases sharply under HII and MII scenarios. This is explained by the increase in yield, see Table 12.

Table 17: Revenue, irrigation costs, other costs (including hired labour) and profits (revenue minus costs, including hired labour and irrigation costs) per technology in different scenarios)

		BU	HII	MII	EX
Variable	**Technology**	**Mio euro**	**Index (BU=100)**		
Revenue	Irrigated	897	389	233	101
	Rainfed	12584	399	254	106
	Total	13481	399	253	106
Irrigation cost	Irrigated	129	123	115	103
Other costs	Irrigated	82	120	113	102
	Rainfed	3151	106	108	106
	Total	3233	106	108	106
Profits	Irrigated	687	471	269	101
	Rainfed	9432	497	303	106
	Total	10119	496	301	106

The profits are unevenly distributed over the Niger River Basin (Figure 16, Figure 17, Figure 18). In this study highest profits are located in Nigeria. Rainfed crops in Niger and Mali are in a similar range, with low profits in the north and intermediate profits in the southern parts of these countries. Niger and Mali differ in profitability of irrigated crops where Mali has higher profits, more in the range of Nigeria. Note the water requirement in Mali seems higher compared to Nigeria (Figure 14).

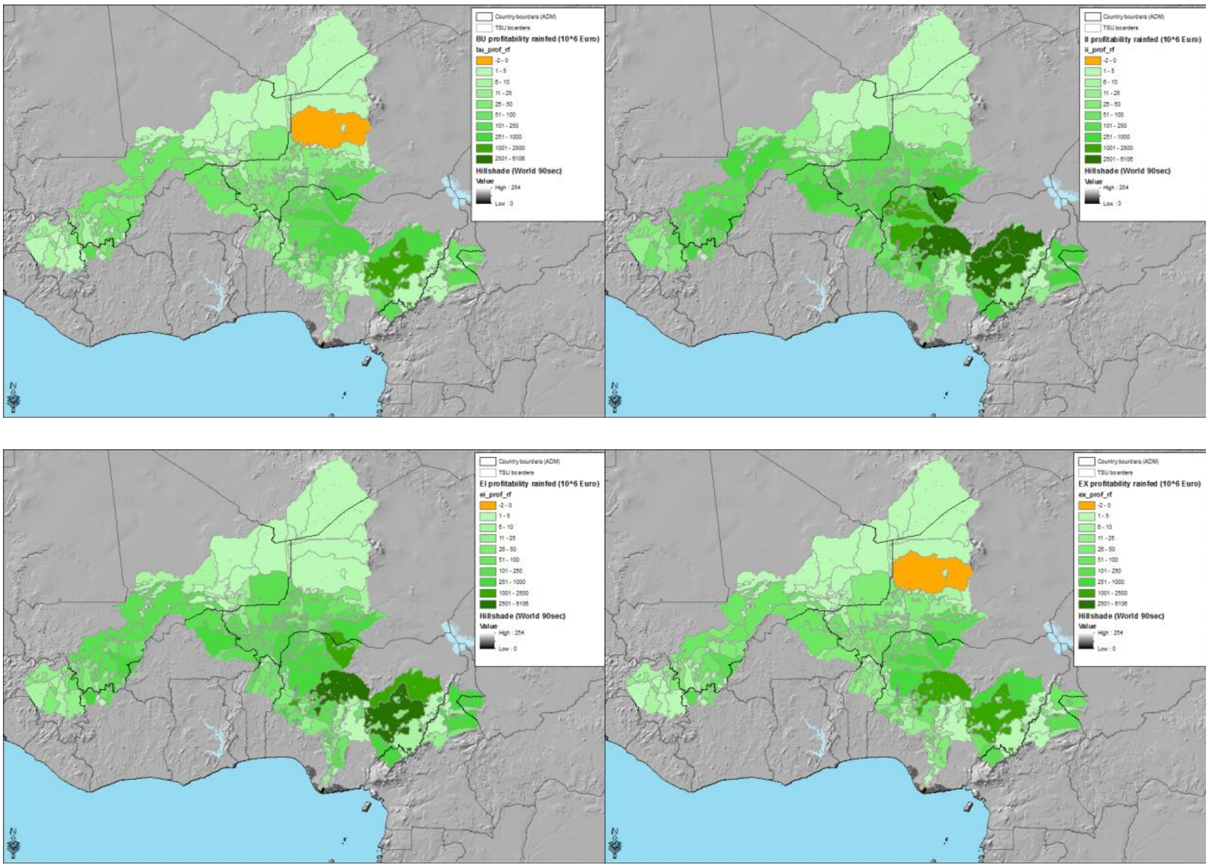


Figure 16: Profitability rainfed crops in 10 ^{6} Euro. BU (top left), HII (top right), MII (low left), EX (low right).

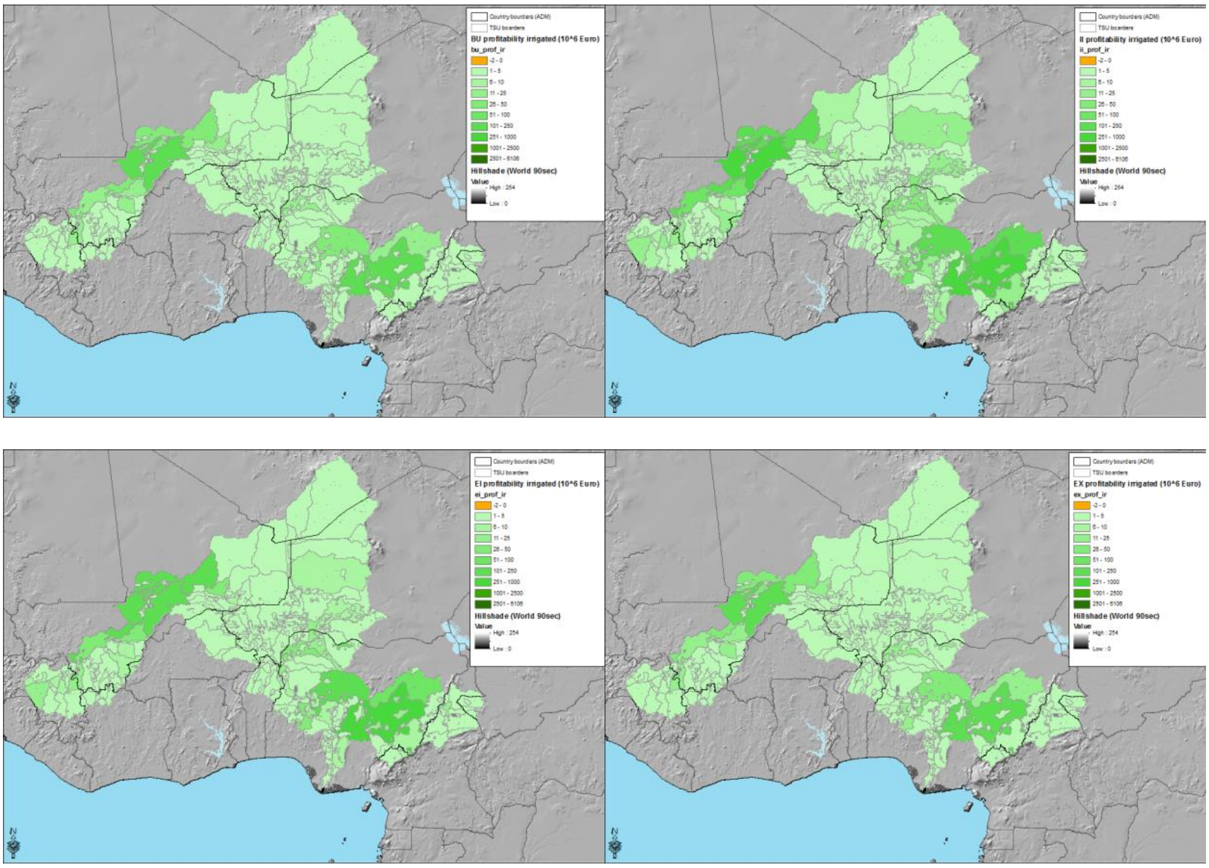


Figure 17: Profitability irrigated crops in 10 ^{6} Euro. BU (top left), HII (top right), MII (low left), EX (low right).

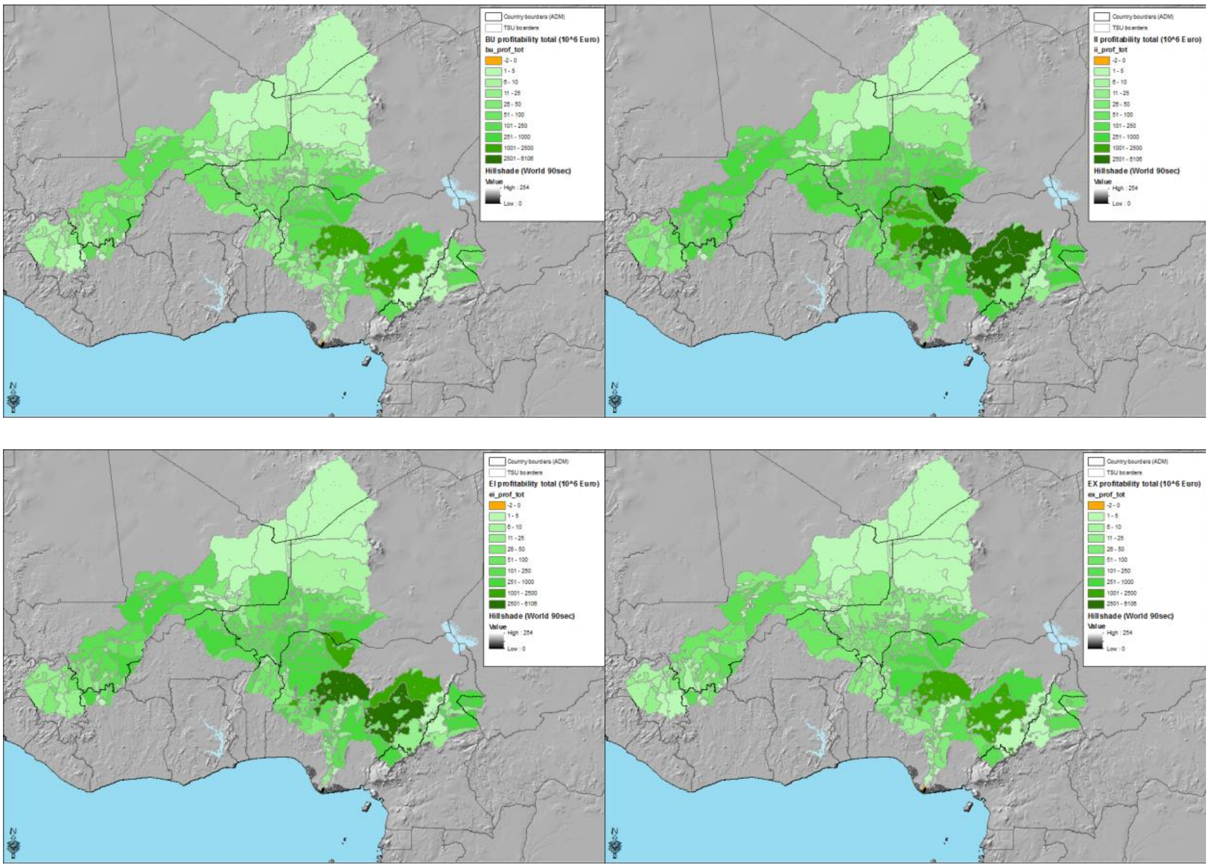


Figure 18: Profitability total crops in 10 ^{6} Euro. BU (top left), HII (top right), MII (low left), EX (low right).

Population and population density, taken from Ceccarelli et al. (2016) was aggregated to TSU resolution. It shows that high profits are correlated with high population levels (Figure 19).

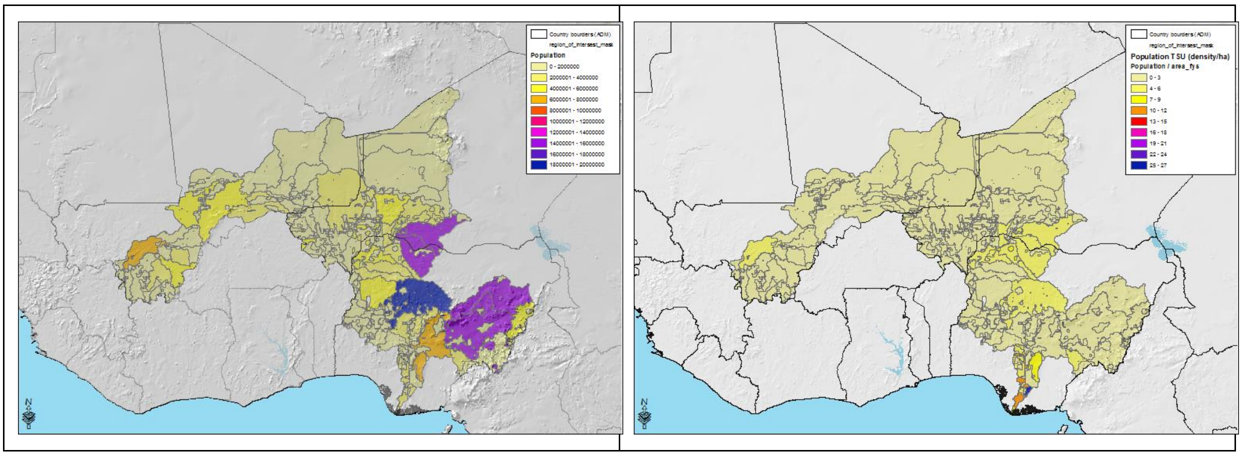


Figure 19: Population and population density, projected to the year 2050 of TSU's in Mali, Niger and Nigeria.

5.6. Selecting the most profitable scenario

The outcome of the model is that in all regions the input intensification scenario is the most profitable.

5.7. Sensitivity analysis: irrigated crop area in scenario HII

A sensitivity analysis was conducted to further investigate the impact of some exogenous model variables on irrigated area in scenario HII. The following adjustments were applied to scenario HII:

a) Decrease of irrigation costs with 50%
b) Increase in total crop area with 10%
c) 50% decrease of total marginal costs related to risk and family labour input, reflecting long term efficiency gains (increased time horizon).
d) 20% increase in output price

Results are presented in Table 18. To add some more context, also the EX index figures from Table 15 are recalled in Table 18. The EX scenario is in fact the BU scenario combined with adjustment b (BU + b).

Adding up all assumptions together, irrigated crop area in scenario HII increased with almost 50% as compared to the irrigated crop area in BU scenario (index 148). Irrigated area of all crops increased, with largest increase found for Fruit and Nuts, Permanent oilseed crops, oilseed crops, sugar crops and vegetables and melon.

Strikingly, the effect of a decrease in irrigation costs with 50% (a) has limited effect except for cereals (+7%) and the fruits and nuts crop group (+5%). When also increasing the allowed total crop area (b), again the effect is limited except for cereals (+9) and the leguminous crop group (+10).

Please note that cereals also increased considerably (+12%) in the extensification scenario (EX = BU + b) compared to BU.

It appeared that especially the marginal costs related to risk and family labour input (c) had a strong positive impact on irrigated crop area. Increasing the output price (d) for some crop groups had a negative impact on irrigated crop area in the HII scenario (cereals and root and tuber crops). This can be explained by limited total land availability and the different impact of price changes on relative **profitability** of the different individual crops and crop groups. Overall output price increase has a relative strong impact on profitability of low margin (rainfed) crops.

Referring to the reservations made in paragraph 5.4 on the comparison of studies, Xie et al (2014) estimate a total irrigation potential expansion of 21 mio ha when fully rolling out their four investigated irrigation technologies (motor pumps, treadle pups, small reservoirs and communal river diversion) over Mali, Niger and Nigeria. Which is about 32.5% of the cultivated land according to FAO AQUASTAT. Xie et al. (2014) also report the impacts of decreasing irrigation costs by 50% and increasing the crop prices by 30%, but only for Sub Saharan Africa as a whole but without testing their combined effects. As in our study, the impact on irrigated area is relatively limited.

Table 18: Total irrigated crop area in BU scenario (ha), HII scenario, HII scenario with 50% decrease irrigation costs (a), 10% increase total crop area (b), decreased marginal costs (c) and 20% increase of output price (d). Index BU =100

	BU	BU + b	HII	HII + a	HII + a + b	HII + a + b + c	HII + a + b + c + d
		Index BU=100					
Rice	308285	101	113	114	115	129	136
Cereals	72971	112	144	151	160	162	156
FruitAndNuts	2362	103	161	166	170	196	197
LeguminousCrops	56	103	91	92	102	105	120
PermanentOilseed Crops	195	102	141	144	147	191	200
OilseedCrops	3165	107	195	196	197	200	200
RootTuberCrops	25651	102	113	116	118	134	129
SugarCrops	41916	101	147	149	151	186	188
FiberCrops	11177	101	106	110	111	120	117
Veget. & Melons	160388	102	124	126	130	156	168
othercrops	30152	100	100	100	100	100	100
Total	**656319**	**102**	**121**	**123**	**126**	**142**	**148**

6. Conclusions

Reviewed recent English and French literature (2010 onwards) on sustainable irrigation potential in the Sahel (i.e. Niger-, Lake Chad-, Volta- and Senegal River basins) points to a significant irrigation potential of Sahelian agriculture. In turn, Sahelian basins irrigation, potential is much higher than current irrigation levels (2% of crop land is irrigated contrasting with 37% in Asia). However, estimates vary greatly depending on the scale of irrigation schemes, whether the resource is surface or ground water, expected and actual irrigation costs but also on determinants of irrigation development. Irrigation potential, not being a static concept, is influenced by synergies between irrigation and other agricultural production technologies and is contingent on levels of other inputs, such as nitrogen fertilizer, in agricultural production. Hence, irrigation investments need to be put in the broader context of productivity enhancement and rural development efforts (Xie, You et al. 2017) and global changes such as urbanisation (Barbier et al. 2011), something which is clearly illustrated by Zorom et al. (2013) regarding Burkina Faso farmers and their perceived vulnerabilities. In their typology of farmers with regards to adaptation strategies to shocks, Zorom et al. (2013) identified that those farmers which have some off-farm income are particularly interested in investing in agriculture if irrigation is made available, whereas other groups may be interested in improving first their access to credit for farm inputs with then a view on irrigation. The way production risks are perceived needs to be clearly identified so that the irrigation systems fostered can be seen as risk-reducing (Burney and Naylor 2012; Burney, Naylor et al. 2013).

Past, and not always successful, efforts in realising the irrigation potential were based on large public irrigation schemes (i.e. river dams and related canals). In a growing number of contexts, investments in small and micro-irrigation systems are identified as more desirable than conventional large schemes. Existing small-scale irrigation systems in the region are known to be developing (Torou et al. 2013) however limited evidence exists. Yet, the realisation of this potential is very sensitive to the costs of irrigation, among the highest in the world, with some technologies more sensitive than others (i.e. small river diversions). The economics of cost-benefit of irrigation should be clearly in favour of investing in irrigation systems, particularly when factoring in the opportunity costs related to complementary or alternative rainfed crops. The example highlighted by Comas et al. (2012) for Mauritanian farmers along the Senegal River Valley are a good illustration of this tension which has materialised through the continuous abandonment of irrigated rice originally supported by irrigation schemes which are gradually falling into disrepair given their maintenance costs which are superior to the marginal gains from the given irrigated crop.

Irrigation systems have been identified as necessary for low endowment SSA farmers (Nazoumou, Favreau et al. 2016). However, the cheaper technology may not be the most recommendable for the most vulnerable farmers in the long run (Burney and Naylor 2012; Burney, Naylor et al. 2013). Cheaper technologies only facilitating marginal efficiency gains may lead to dis-adoption because of weak economic returns. Moreover, probable climate change impacts and other global changes (e.g. global energy prices) will make improved water saving technologies more valuable over time even if more expensive upfront both financially and organisationally speaking (Burney and Naylor 2012).

Uncertainties surrounding the impact of climate change on rainfed agriculture have renewed interest in evaluating irrigation prospects in the region. However there is not a consensus surrounding climate change model results. Some predict that the Sub-Saharan region becomes wetter, others drier but most models seem to predict the later conditions that might cause, for example, the Nigerian Sahel to experience a shortening of length of the growing season and a drop in yields of rainfed agriculture. There is strong consensus that in the coming decades, continued climate change will result in more unpredictable weather accompanied by temperature rise in the Sahel. This warming will have considerable impact on Sahel agriculture, as temperature changes have a much stronger impact on yields than precipitation changes.

The Niger Basin's irrigation potential was also assessed through modelling. The model uses static biophysical and socio-economic indicators in model optimising profits of mainly small holder farms under 4 possible agricultural scenarios with varying agriculture productivity levels; namely, Business as Usual (BU), High Input Intensification (HII), Medium Input Intensification (MII), and simple expansion of agriculture frontier or Extensification (EX). The basin was divided into 201 regions for which we estimated total crop area, yields, crop prices, crop suitability, nutrient requirement, irrigation and other costs. In general, irrigated area does not evolve much between scenarios mainly because of high productions costs associated with increased irrigation.

Irrigation shares generally remained low in all scenarios. Depending on the scenario and region, they increased or decreased relatively to the business as usual situation. The highest increase in the share of irrigated area with respect to total agricultural area is found in the most productive in terms of agricultural yields scenario[19]. The share of irrigated area rises from about 1.47% in the business as usual scenario to 1.79% in the so-called High Input Intensification scenario to 2050. In turn, the Extensification scenario, irrigation shares show a relatively decrease in almost all regions, -0.08% absolute change on average but total irrigated area increased because of the increase in agricultural area. The Medium Input Intensification scenario scores in-between with +0.12% absolute change of the share of irrigated area in total agricultural area. Irrigation requirement increased or decreased proportionally to the above results. In general, although it appeared profitable to increase total acreage of irrigated crops, irrigated area is quite sticky in the model because of high costs and high risks associated with increased irrigation. This explains the relative limited increase in irrigated area while the increase in rainfed crop areas can be considerably larger (+9% for the EX).

The high profitability of rainfed agriculture under the High Input Intensification scenario is caused by the small difference between high input rainfed and high input irrigated yields. Results would be more in favour of irrigation techniques if the gap would be higher. In this study we did not have the opportunity to compare with or create alternative yield datasets.

Although irrigation potential is theoretically large, investing in both irrigated and rainfed input intensification is most profitable. The results for potential are in the range of 0.6-09M hectares under the most agriculturally productive scenario (HII) are significantly lower than previous estimates and depend on assumed irrigation and input costs. Existing estimates indicate that between 1% to 5% of the total crop area in the basin is irrigated (0.55-0.9 M ha). In turn, irrigation potential could reach 1.5-2.9M ha with an associated expansion of the total agricultural area (ABN & BRL 2007; FAO 1997). The specific strengths of this new estimation are that of using input costs from recent agricultural surveys (i.e. LSMS-ISA). Its main limitations are that is does not distinguish between irrigation technologies and related costs; and that agriculture expansion is exogenously determined. See Figure 20 (below) for a visual comparison on estimates.

[19] This performance is estimated ignoring possible implications for wild biomass production and other environmental impact such as salinity levels of groundwater reserves),

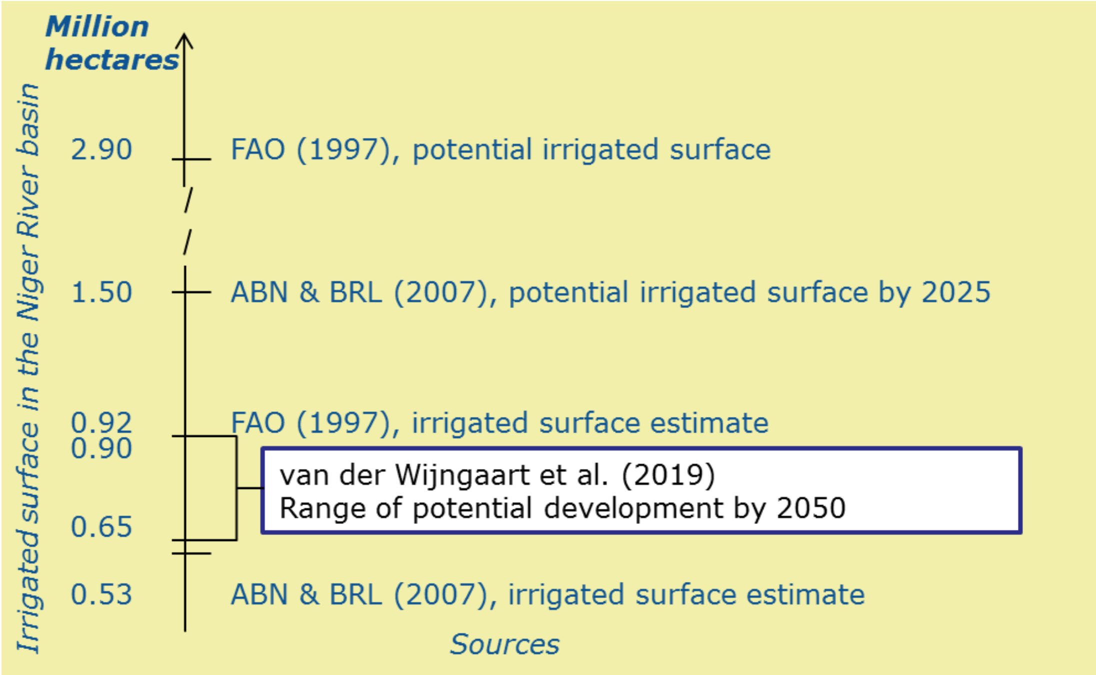


Figure 20 Irrigated crop land, estimates of current and potential surface. Sources FAO (1997); ABEN & BRL (2007); New estimate ranges of potential under high input-intensification (HII) scenario.

According to studies discussed in the literature review of this report, and according to our own modelling, investments are expected large, while rates of return are probably low. That said, a rigorous comparison with other studies remains very difficult and only an approximation can be made. Reference studies cover different regions, include different irrigation technologies, use different data sources, and are based on different model components and scenario assumptions. Potentially these factors all contribute to differing outcomes. Having mentioned this, other studies such as by Pavelic (2013), Altchenko et al. (2015) and Xie et al (2014) tend to estimate irrigation potential much higher than our study. When comparing irrigation requirement from our study with available water from a different source such as the runoff dataset from UNH-GRDC, some major TSU's in Mali have a negative balance which deepen under an expansion scenario. According to this comparison, more northern regions of Mali and Niger have a neutral balance due to low water requirements and TSU's in Nigeria have a positive balance.

Profits increase sharply when inputs are intensified, mostly due to intensification and increased yields. Yet, profits vary considerably between regions. Nigeria shows the highest profits in all agricultural scenarios.

A model sensitivity analyses was executed to estimate the impact of a decrease in irrigation costs, increase in allowed area expansion, decrease of total marginal costs related to risk and family labour input, and increase in output prices. It revealed that the model was most sensitive to the decrease of total marginal costs. Adding up all shocks, it would lead to a relative increase of 48% in total irrigated crop area of the input intensification scenario. Whereas the standard input intensification scenario itself results in a total relative increase of 21%.

The specific strengths of this new estimation are that of using input costs from recent agricultural surveys (LSMS-ISA) imposing realistic constraints to the physical potential of irrigation. It has important limitations, however. The model accounts for only two technologies and related costs (i.e. irrigation and rainfed agriculture), while profits are expected to be very different for various irrigation technologies. Yet, the expansion of agriculture is exogenously determined.

The development of irrigation in the Sahel and in the Niger River basin in particular is a key intervention area for agriculture and development policy in general.

However, performing rainfed agriculture retains the larger potential for development when looking at costs and overall potential profits. Moreover, support to the development of irrigated agriculture needs to be fully integrated with the support to agriculture in general. For example, the potential of irrigated agriculture is directly linked to the quality access to inputs (esp. fertilisers) given the importance of improved input management in realising irrigation agriculture potential. This is also the case for functioning supply chains in general so to reduce losses of potentially more valuable produce from irrigated agriculture.

The development of irrigation in the Sahel and in the Niger River basin in particular is a key intervention area for agriculture and development policy in general. Current policy identifies irrigation development as an instrument fostering food security. However, from the angle of optimization, rainfed agriculture retains the larger potential for development when looking at costs and overall potential profits. Moreover, support to the development of irrigated agriculture needs to be fully integrated with a relevant and adapted support to agriculture in general, particularly with regards to how it mitigates risk. Access to irrigation is expected to expand farmers' production opportunities. It mitigates production risks, even in low quantities as crop-saving irrigation. By reducing risk, it encourages farmers to make more intensive use of inputs and land. Moreover, this dynamic effect is also influenced by the type of irrigation systems accessed. For example, the literature has identified that farmers which have some off-farm income are particularly interested in investing in agriculture if irrigation is made available, whereas other groups may be interested in improving first their access to credit for farm inputs with then a view on irrigation (Zorom et al. 2013) . How production risks are perceived need to be clearly identified so that the irrigation systems fostered can be seen as risk-reducing. Functioning supply chains would also make irrigation more profitable as they reduce losses of potentially more valuable products from irrigated agriculture and enhance market access.

Access to irrigation is expected to expand farmers' production opportunities. It mitigates production risks, even in low quantities as crop-saving irrigation. By reducing risk, it encourages farmers to make more intensive use of inputs and land. Moreover, this dynamic effect is also influenced by the type of irrigation systems accessed. For example, irrigation "on-demand" fosters turning part or all farming towards high-value crops. Also, motor-pump irrigation was favoured by many farmers, and although it may not systematically translate in higher productivity than alternative systems, it inspires confidence in farmers to intensify more, take greater risks and open up to the market (Shah, Verma et al. 2013).

Full consideration of the role of small-scale irrigation, both as a developing and potential technology, beyond traditional larger-scale approaches is key. Recently registered regional increases in groundwater storage have been associated to diffuse recharge, partially compensating for groundwater withdrawal associated with irrigation development. Hence, hinting at some level of sustainability in the use of groundwater for small-scale irrigation in the Sahel, despite the risks associated with salinization. That said, striving to improve data collection and monitoring water use and availability remains critical.

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- CILSS (http://www.cilss.bf/)

Websites

l'Autorité du bassin du Niger (ABN) (http://www.abn.ne)

Club du Sahel et de l'Afrique de l'Ouest (http://www.oecd.org/swac/)

Observatoire du Sahara et du Sahel (http://www.oss-online.org/)

AGRHYMET (http://www.agrhymet.ne/)

Economic Community of West African States- ECOWAS (http://www.ecowas.int/)

Institut du Sahel (http://www.insah.org/)

Global Yield Gap Atlas (http://www.yieldgap.org/web/guest/home)

FAOAfrica (http://www.fao.org/africa/resources/publications/en/)

UNEP, 2012, AFRIQUE: ATLAS DE I'EAU

https://na.unep.net/atlas/africaWater/downloads/Africa_Water_Atlas_Executive_Summary_French.pdf

List of abbreviations and definitions

AEZ	Agro Ecological Zone
AfDB	African Development Bank (or BAD in French)
AS	Agricultural scenario
AWM	Agricultural Water Management
BU	Business as Usual (scenario)
BAD	Banque Africaine de Dévelopment (or AfDB in English)
CAADP	Comprehensive Africa Agriculture Development Programme
CC	Climate change

CGIAR-TAC	Consultative Group on International Agricultural Research – Technical Advisory Committee
CCAFS	Climate Change, Agriculture and Food Security
CHG	Climate Hazards Group
CHIRPS	Climate Hazards Group InfraRed Precipitation with Station data
CILSS	Comité permanent Inter-Etats de Lutte contre la Sécheresse dans le Sahel (Interstate Committee for Drought Control in the Sahel)
CIWA	Cooperation in International Waters in Africa
DAP	Di-ammonium phosphate
DREAM	Dynamic Research Evaluation for Management
EX	Expansion (scenario)
FAO	Food and Agriculture organization of the United Stations
GADM	Global Administrative Areas
GAEZ-LGP	Global Agro-Ecological Zone Length of Growing Period
GAUL	Global Administrative Unit Layers
GEnS	Global Environmental Stratification
GIS	Geographic Information System
GLI	Global Land Initiative
GYGA	Global Yield Gap and Water Productivity Atlas
HII	High Input Intensification (scenario)
HCAEZ	Harvest Choice Agro-ecological Zone
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFAD	International Fund for Agricultural Development
IFPRI	International Food Policy Research Institute
IPCC	Intergovernmental Panel on Climate Change
IRR	internal rate of return
IWMI	International Water Management Institute
LSMS-ISA	Living Standards Measurement Study - Integrated Surveys on Agriculture
MII	Medium Input Intensification (scenario)

NEPAD	New Partnership for Africa's Development
NLP	Neuro-Linguistic Programming
NPK	Nitrogen (N), Phosphorus (P), and Potassium (K)
PMP	Positive Mathematical Programming
PPP	Public-Private Partnership
SAGE	Centre for Sustainability and the Global Environment
SSA	South Saharan Africa
SWAT	Soil & Water Assessment Tool
TS	Technical Specifications
TSU	Target Spatial Unit
UNEP	United Nations Environment Programme
USAID	Lead U.S. Government agency that works to end extreme global poverty and enable resilient, democratic societies to realise their potential.
WUE	Water Use Efficiency

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Appendices

ANNEX I: Review of the literature summary of source.

You et al., 2011 used a biophysical and socioeconomic approach to analyse the irrigation potential and investments needs in Africa. This paper provides the most comprehensive approach available on irrigation potential in Africa and the Sahel. Both large, dam-based and small-scale irrigation investment needs are analysed based on agronomic, hydrologic, and economic factors. They follow five steps that are applied to the seven agro-ecological zones in Africa:

1. Make estimates of the area and yield distributions (1-10 km res. global grid)
2. Calculate runoff (water available for irrigation)
3. Identify potentially irrigable area based on topography (assuming gravity fed irrigation) and associated water delivery cost
4. Maximise annual net revenue due to irrigation expansion across potential areas and crops. This step requires information on crop prices, costs of production; crop water requirements, output of crop; and the amount of water (either from runoff or stored behind the dam) available for irrigation net of other, prior claims such as hydropower, industrial, and household water consumptive basin water use.
5. Calculate Internal Rate of Return (IRRs) to irrigation. For small-scale irrigation, profitable areas are identified by pixel. For large-scale irrigation, IRRs are calculated for each dam.

Conclusions can be summarised as:

- The results for large- and small-scale irrigation present a striking contrast. Although the total area expansion potential is small for small-scale irrigation, IRRs are considerably higher. The average IRR for large-scale irrigation is 6.6 percent, versus an average IRR of 28 percent for small-scale irrigation. The higher an IRR value, the more desirable the irrigation investment is.
- The potential for irrigation investments is highly dependent upon geographic, hydrologic, agronomic, and economic factors. The results are sensitive to assumptions about the unit costs.
- The potential for expansion is significant in Sub-Saharan Africa. Combined results of the dam-based and small-scale analyses are shown in Table 19.

Table 19: Potential increase and investment needs for small-and large-scale irrigation, positive IRR (You et al., 2011)

Country / region	Large scale		Small scale		Total increase in irri. area (1000 ha)
	Investment cost US$M	Increase in irri. area (1000ha)	Investment cost US$M	Increase in irri. area (1000 ha)	
Nigeria	6.185	3.169	12.942	2.505	5.674
Mali	370	189	1.559	302	491
Guinea	2.355	1.207	603	117	1,324
Senegal	1.066	546	617	119	665
Niger	130	67	658	127	194
Burkina Faso	536	275	505	98	373
S-Sahelian*	3.160	1.619	6.536	1.265	2.884

*Sudano-Sahelian: Burkina Faso, Cape Verde, Chad, Djibouti, Eritrea, The Gambia, Mali, Mauritania, Niger, Senegal, Somalia, Sudan.

In terms of country potential, Nigeria stands out as having particularly great potential. The country has the largest potential for both small- and large-scale irrigation investments, at 5.7 million ha, accounting for almost a quarter of total area potential. For small-scale irrigation, rates of return are highest in the Sudano-Sahelian zone. Mali stands out as a particularly lucrative site for investments.

Market access conditions have been shown to be critical for irrigation development to succeed. Whereas they are explicit in the case of small-scale irrigation, they will also play an important role for large-scale irrigation.

Xie et al., 2014 looked into the potential for expanding smallholder irrigation in Sub-Saharan Africa (SSA). Results are grouped per SSA region: Central Eastern, Gulf of Guinea, Southern, and Sudano–Sahelian. This paper provides a good, solid overview for small-scale potential based on an integrated approach. Four expansion scenarios are looked at: motor pumps, treadle pumps, communal river diversion, and small reservoirs. An integrated modelling system that combines GIS data analysis, biophysical and economic predictive modelling, and crop mix optimisation techniques is used. Irrigation expansion was simulated in 4 steps:

1. Initial estimates of areas with application potential using GIS, environmental suitability and demographic data
2. SWAT modelling (water availability, water use and crop yield for different irrigation methods) and DREAM[20] modelling (economic returns)
3. Use IWMI scenarios on how agricultural production systems can be reshaped by smallholder irrigation, taking into account annual application rate of nitrogen fertilisers (nutrients)
4. Apply a crop mix optimisation approach.

Two types of results are shown:

1. Expansion potential baseline conditions (baseline commodity price and cost values). These results indicate a large potential for the expansion of smallholder irrigation.
2. Expansion potential with alternative irrigation costs and crop prices.

Ad 1) Regarding expansion potential baseline conditions, the study revealed a considerable potential for profitable smallholder irrigation expansion (Table 20).

Table 20: Estimated potential expansion of smallholder irrigation under baseline conditions

Technology	Smallholder irrigated area (1000 ha)
Motor pumps Sudano–Sahelian region*	3062
Treadle pumps Sudano–Sahelian region	2348
Communal river diversion Sudano–Sahelian region	1074
Small reservoirs Sudano–Sahelian region	1969

*Sudano–Sahelian region includes Burkina Faso, Chad, Eritrea, Mali, Mauritania, Niger, Senegal, Somalia, Sudan and The Gambia

Ad 2) Regarding expansion potential that take into account alternative costs, Xie et al conclude that final expansion potential depends on irrigation technology costs and commodity price developments. Thus estimated irrigation expansion potential is *(highly)*

[20] Wood et al. 2005. Wood, S., You, L., Baitx, W., 2005. Dynamic Research Evaluation for Management(DREAM). IFPRI, Washington, D.C.

sensitive to irrigation costs and crop prices. An increase in initial agricultural commodity prices and a decrease in irrigation costs improve the profitability of irrigation.

A map is provided on river basins with binding water availability constraints obtained from crop-mix optimisation for each of the 4 technologies. It shows that in terms of environmental impacts, although the water consumption of expanding smallholder irrigation is not large compared to available renewable water resources, water scarcity will constrain expansion in many regions. The basins with binding water availability constraints will be more likely to be exposed to adverse environmental risks resulting from irrigation expansion (i.e. farmers may use the portion of surface runoff, which is preserved to meet environmental flow requirements, undermining the sustainability of aquatic environments).

Burney et al., 2013 provide an overview of distributed irrigation across SSA and its advantages. Provides a short overview on historical development and the way forward for small scale irrigation. It reflects on references where small scale distributed irrigation has larger expansion potential than large centralised schemes and offers much greater potential profits. A number of benefits of distributed irrigation —particularly when it is deployed at a large scale—offers a number of important benefits over centralised irrigation infrastructure: They outperform in terms of unit cost and performance; They have a larger expansion potential as large centralised schemes and offers much greater potential profits; And they offer substantial environmental benefits over large centralised systems. The expansion potential and potential profits in SSA are confirmed by You et al. (2010) and Giordano (2012), IWMI study. Given the untapped potential of distributed smallholder irrigation systems, more attention should be given to this in planning investments by international donors and governments.

Pastori et al., 2014 developed a high resolution GIS database integrated with a biophysical model able of simulating impacts of nutrient and water limitation on crop production. The added value of this report is the use of fertiliser scenarios and the effect to crop growth. The study produces maps (Figure 21) of actual and potential irrigation areas, with average volumes applied under different scenarios. For each country, an indication is provided if crop production is Nitrogen limited or Water limited.

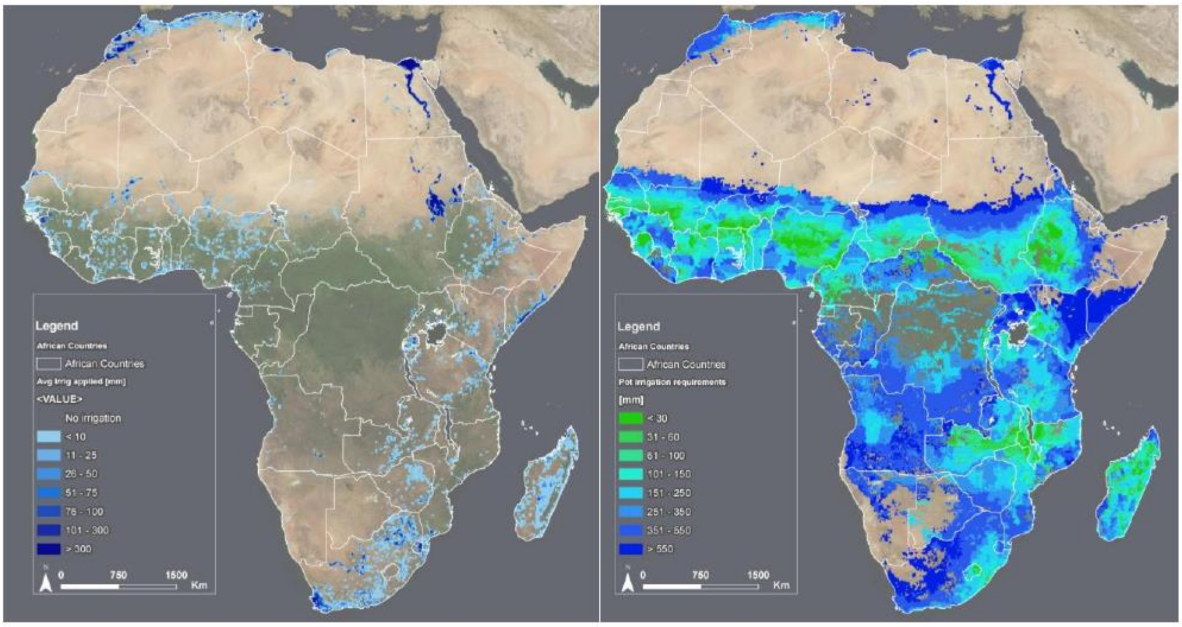

Figure 21: Example Figure Actual and potential irrigation areas and average volumes applied under different scenarios (Pastori et al. 2014)

The study at continental scale showed that the potential increase of crop production in Africa is strictly linked with fertilisation, but above all with irrigation issues and pointed out a potential high increase of environmental impact (= less sustainable). Currently irrigation practices are characterised by a low use of fertilisers, resulting in minor environmental impacts.

Pavelic et al., 2013 provide country level estimates of the irrigation potential for smallholder groundwater irrigation in SSA. The abundance of groundwater resources of SSA is generally well recognised, but quantitative estimates of their potential for irrigation development are lacking. This paper derives useful estimates of irrigation potential using a simple and generic water balance approach and data from secondary sources for 13 countries (Table 21). Even with conservative assumptions and accounting for water demands from other sectors, including the environment, a 120-fold increase (by 13.5 million hectares) in the area under groundwater irrigation is possible for the countries considered.

Table 21: Summary of potential new areas under irrigation and the number of households affected (Pavelic et al. 2012)

	New areas under irrigation (10^6 ha) for irrigation water demand of:			Min. and max. number of households affected (millions)
	100 mm/y	500 mm/y	1000 mm/y	
Burkina Faso	4.1 ± 1.9	0.81 ± 0.38	0.41 ± 0.19	0.43 – 12
Ethiopia	7.1 ± 4.0	1.4 ± 0.8	0.71 ± 0.40	0.62 – 22
Ghana	12.5 ± 5.3	2.5 ± 1.1	1.2 ± 0.5	1.4 – 36
Kenya	0.50 ± 0.22	0.104 ± 0.04	0.05 ± 0.02	0 – 2.0
Malawi	0.86 ± 0.50	0.17 ± 0.10	0.086 ± 0.050	0.072 – 2.7
Mali	9.4 ± 4.0	1.9 ± 0.8	0.94 ± 0.40	1.1 – 27
Mozambique	7.9 ± 3.4	1.6 ± 0.7	0.79 ± 0.34	0.91 – 23
Niger	0.59 ± 0.50	0.12 ± 0.10	0.06 ± 0.05	0.017 – 2.2
Nigeria	38.7 ± 17.4	7.7 ± 3.5	3.9 ± 1.7	4.3 – 112
Rwanda	3.2 ± 1.4	0.65 ± 0.28	0.32 ± 0.14	0.37 – 9.3
Tanzania	13.5 ± 6.0	2.7 ± 1.2	1.4 ± 0.6	1.5 – 39
Uganda	13.6 ± 5.8	2.7 ± 1.2	1.4 ± 0.6	1.6 – 39
Zambia	23.1 ± 9.4	4.6 ± 1.9	2.3 ± 0.9	2.7 – 65
Total	**135.1 ± 60.1**	**27.0 ± 12.0**	**13.5 ± 6.0**	**15.0 – 390**

One country has high potential (Zambia), seven have moderate potential (Ghana, Mali, Mozambique, Nigeria, Rwanda, Tanzania and Uganda), and five have medium to low potential (Burkina Faso, Ethiopia, Kenya, Malawi and Niger).

Using the approach, physical boundary conditions can be established on the cultivated area that may be used for irrigation. Note that uncertainties exist on the groundwater-recharge data and the environmental groundwater requirements.

Altchenko and Villholth, 2015 derive an Africa continent wide map of groundwater irrigation potential, indicated in terms of fractions of cropland potentially irrigable with renewable groundwater. Their high quality paper presents an annual groundwater balance approach using 41 years of hydrological data. The fraction of groundwater recharge is based on fulfilling present human needs and environmental requirements, while disregarding socio-economic and physical constraints in access to the resource. Due to uncertainty of groundwater environmental needs, three scenarios for recharge were used. Current dominating crops and cropping rotations and associated irrigation requirements in a zonal approach were applied. Results show a heterogeneously distributed groundwater irrigation potential across the continent. The study shows that significant potential exists in the semiarid Sahel which could support poverty alleviation if developed sustainably and equitably.

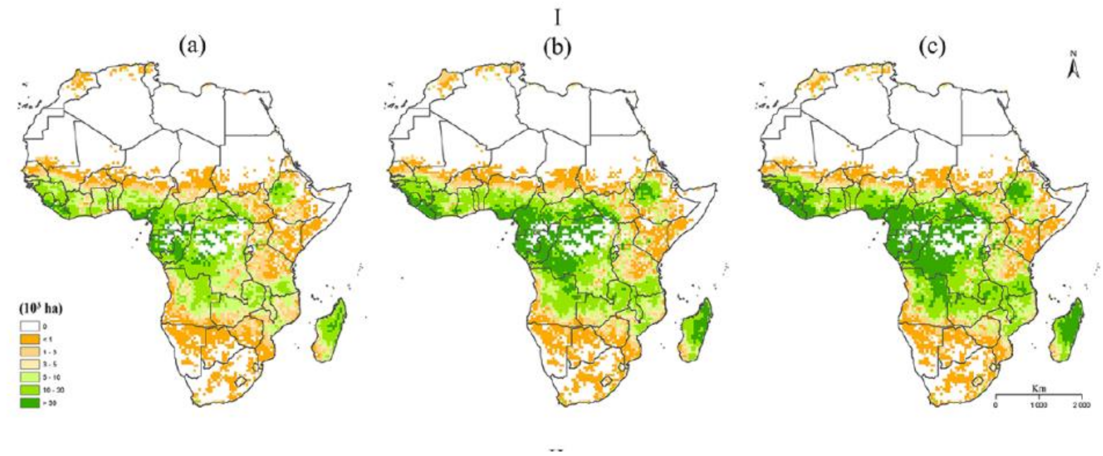

Figure 22: Example Map from study: Total area irrigable with groundwater inside a cell for the 3 scenarios (Altchenko and Villholth, 2015)

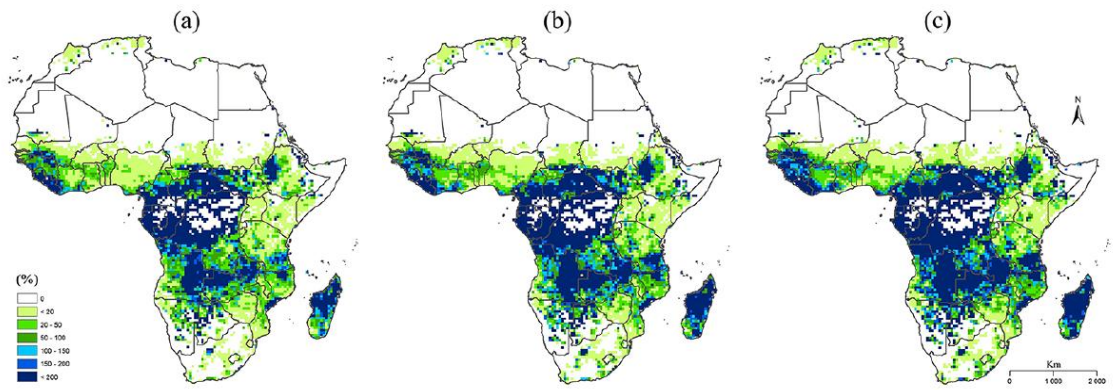

Figure 23: Example Map from study: Proportion of cropland irrigable with groundwater for the 3 scenarios (Altchenko and Villholth, 2015)

A country level table results from the study (Table 22):

Table 22: Gross groundwater irrigation potential and cultivated area per country in Africa for 3 environmental scenarios (Altchenko and Villholth, 2015)

Country	Area of cropland irrigable with groundwater (1000 ha)		
	1 (30 %) environmental needs	**2 (50 %) environmental needs**	**3 (70 %) environmental needs**
Burkina Faso	268	188	108
Guinea	2751	1962	1172
Mali	787	559	331
Niger	19	12	6
Nigeria	6287	4446	2606

Not included yet in this study (should be in further study) are hydrogeological conditions, groundwater accessibility, soils, and socio-economic factors.

Pavelic et al., 2012 assess the potential of groundwater for small scale irrigation expansion for 2 case studies (Niger and Ghana/Burkina Faso). According to national-level figures from a cross-section of 16 SSA countries, groundwater is being used to irrigate less than 1% of the arable land. There is emerging evidence that farmers are increasingly resorting to groundwater for irrigating high-value crops. Across much of the region, very little is known about the physical extent, accessibility and development potential of groundwater. The region is characterised by a scarcity of data and general lack of knowledge on groundwater systems.

The conference paper presents for 2 case studies (basin in Niger and basin in Ghana/Burkina Faso), a simplified methodological framework that aids in the estimation of upper limits of groundwater development for irrigation in terms of volumes of abstraction and irrigated area.

Results show that for both sites that there is significant potential for further groundwater development for irrigation expansion. It also shows that groundwater availability will restrain irrigation development rather than land area. The lesson from two case studies is that the untapped development potential may be realised with sufficient understanding of the demand-and-supply balance, supported by the inclusion of monitoring and evaluation systems. For the case study in Niger, about a 50% increase in the area under irrigation for the country can be realised.

Namara et al., 2011 look at the current constraints in irrigation development and estimate the irrigation potential for Ghana. Despite considerable potential for development (gross estimated irrigable area 1.9 million ha) and the emphasis placed on irrigation development in many plans, less than two percent of the total cultivatable area in Ghana is irrigated. This IFPRI report presents a good, integrated approach to quantify:

1. Ghana water resources
2. Characterisation of irrigation schemes (typology)
3. Economics of irrigated agriculture: investments costs irrigation.

In Ghana, the cost of irrigation development (and also rehabilitation) is higher than in other African countries. Capacity underutilisation is a major problem in many existing irrigation facilities. The potential areas that can be developed in each of the public irrigation schemes are much higher than the developed or equipped areas. In addition, only a fraction of the developed or equipped area is actually cultivated. Rehabilitation of many of the irrigation schemes is long overdue. Results show that the irrigation potential for Ghana is huge, however estimates of the irrigation potential diverge wildly.

Oyebande et al., 2010 synthesise in their paper the state of art research regarding climate change impact on water resources in West Africa economies. They analysed the climate change impact on water resources in West Africa for the cases of the Senegal, Niger and Volta Basins. Climate variability and change directly affects West African national economies in general and those of the Sahelian States in particular. This is due to the significant contribution of rainfed agriculture; the poor status of water management; and the poor replenishment of reservoirs on which some countries depend heavily.

Climate change will have an impact on available water resources and e.g. the growing period. But from the climate studies, the climatic future of the mentioned basins is uncertain and imperatively no single scenario can be provided at present. While temperature is almost certain to rise, rainfall may increase or decrease. Due to the uncertainties, no clear conclusion can be drawn regarding the impact of climate change to irrigation potential in West Africa.

Dittoh et al., 2010 present in their report a future direction for irrigation development in the West African Sahel based on an assessment of the extent of use and impacts of micro irrigation technologies in Burkina Faso, Mali, Niger and Senegal. Participatory rural appraisal and participatory impact assessment tools were used to obtain information from about 200 small irrigators in 22 communities in the four countries.

Drip irrigation in the form of the "African Market Garden" is a proven technology that has the potential to drastically reduce poverty in the Sahel (Sahel Programme ICRISAT). The study has shown that it is profitable to the farmers with convenience (higher impacts) on several farming related factors. The cost of establishing a viable smallholder drip irrigation system is however above the capabilities of small farmer groups. The study recommends to institute modified public-private partnership (PPP) methodologies of funding and management of farmer-group (micro) drip irrigation systems to ensure viable and sustainable systems in the Sahel.

Kadigi et al., 2012 present a policy brief on irrigation and water use efficiency in Sub-Saharan Africa to determine factors which can determine success or failure of irrigation schemes. It provides a good overview of the main factors identified as key factors that led to the failure of past schemes:

1. Irrigation schemes were more expensive than they needed to be.
2. Poor initial planning led to poor operations.
3. Farmers did not see the benefits of investing in irrigation.
4. Expectations of yield improvements were overly optimistic.
5. Infrastructure was not maintained and fell into disrepair.

MacDonald et al., 2012 provided estimated groundwater storage for African countries, including the Sahelian countries. There is little quantitative information on groundwater resources in Africa, and groundwater storage is consequently omitted from assessments of freshwater availability. Although assumptions made, the paper is useful as it presents the first quantitative continent-wide maps of aquifer storage and potential borehole yields in Africa. The quantification is based on an extensive review of available maps, publications and data. These maps help to support the development of groundwater-based irrigation strategies.

Not key references but relevant studies are summarised here:

Giordano et al., 2012 review current smallholder agricultural water management (AWM) practices and conclude that the potential for growth in the sector is enormous, particularly in SSA where there is significant scope for expanding the area under irrigation. Estimates show that increasing the number of small reservoirs here could reach 369 million people and generate net revenues of US$ 20 billion annually. Meanwhile, expanding the quantity of motor pumps could benefit 185 million people and generate net revenues of US$ 22 billion annually.

World Bank, 2013 addresses the importance in sustainable irrigation development of taking into account risks that agriculture systems are facing. There is a need to consider risks and volatility as the new normal and resilience as cornerstone for transformative growth in agriculture in the Sahel. A landscape approach is opted to address the challenge of agriculture in the Sahel. A landscape approach describes interventions at spatial scales that attempt to optimise the spatial relations and interactions among a range of land cover types, institutions, and human activities in an area of interest. Six interventions are proposed:

1. Massively Scaling-Up Irrigation Investments
2. Facilitating Wide-Spread Adoption of Sustainable Land and Water Management (SLWM) Practices in Rainfed Agriculture
3. Enhancing Pastoralists Development and Livestock Management
4. Accelerating Adoption of Resilient Agricultural Technologies: Drought Tolerant Crop Varieties
5. Improving Post-Harvest Management Practices and Market Access and Integration
6. Improving Emergency Preparedness.

Mueller et al., (2012) proof that global yield variability is heavily controlled by fertiliser use, irrigation and climate. Crop production in the Sahel region is mostly nutrient limited. The crucial role of nutrient and water management in pathways towards sustainable intensification is described in their Nature publication. Yield gaps are analysed and compared to crop production inputs. West Africa stands out as hotspots of nutrient limitation for e.g. maize.

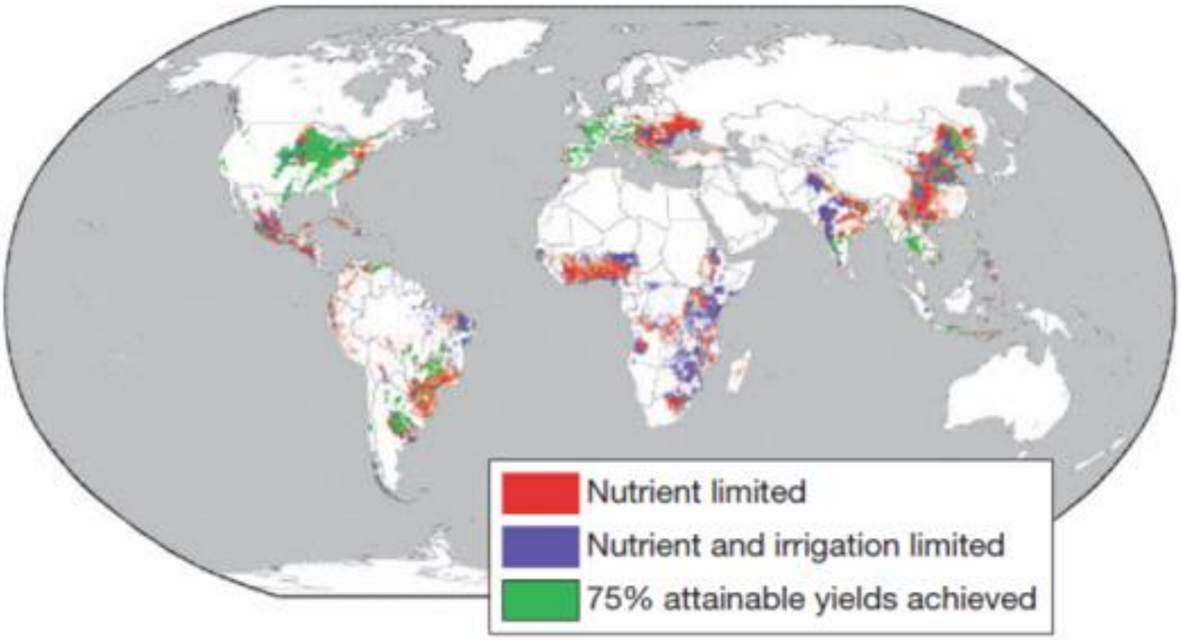

Figure 24: Main limitation by Mueller et al., (2012)

Ofusu et al., 2012 analysed different irrigation technologies in the White Volta (northern Ghana and southern Burkina Faso) for a comparative analysis of their productivities, in terms of crop yield, water use and financial returns. The results show that adequate fertiliser application is the major contributor to irrigation productivity. The impact that an irrigation technology has on the irrigation productivity has got to do with the control over the water resources by the farmer and the size of the farm irrigated by the technology. Farmer driven technologies and endogenous irrigation development provides a strong backing that the way forward in SSA is for governments to create policies that facilitate poor farmers becoming irrigation entrepreneurs. Such policies should aim to enhance the reliability of markets (both input and output) as the driving force, and facilitate people's access to land and water.

ANNEX II. GAEZ crop list

no	Name	Crop code in table	no	Name	Crop code in table
1	Wheat	whe	23	Pigeon pea	pig
2	Wetland rice	rcw	24	Soybean	soy
3	Indica dryland rice	rcd	25	Sunflower	sfl
4	Maize	mze	26	Rape	rsd
5	Barley	brl	27	Groundnut	grd
6	Sorghum	srg	28	Oil palm	olp
7	Rye	rye	29	Olive	olv
8	Pearl millet	pml	30	Jatropha	jtr
9	Foxtail millet	fml	31	Cabbage	cab
10	Oat	oat	32	Carot	car
11	Buckwheat	bck	33	Onion	oni
12	White potato	wpo	34	Tomato	tom
13	Sweet potato	spo	35	Banana	ban
14	Cassava	csv	36	Citrus	cit
15	Yams	yam	37	Coconut	con
16	Sugarcane	suc	38	Cacao	coc
17	Sugarbeet	sub	39	Cotton	cot
18	Phaseolus bean	phb	40	Flax	flx
19	Chickpea	chk	41	Alfalfa	alf
20	Cowpea	cow	42	Coffee	cof
21	Dry pea	not avail for download	43	Tea	tea
22	Green gram	grm	44	Tobacco	tob

ANNEX III. MAPSPAM crop list

no	Name	no	Name
1	banana	22	oil_palm
2	bean	23	plantain
3	cowpea	24	potato
4	chickpea	25	rice
5	lentil	26	sorghum
6	pigeonpea	27	sugar_cane
7	cassava	28	sugar_beet
8	cocoa	29	sweet_potato
9	coconut	30	tea
10	coffee_arabica	31	yam
11	coffee_robusta	32	fibers_other
12	cotton	33	oil_crops_other
13	groundnut	34	pulses_other
14	maize	35	rapeseed
15	fruit_tropical	36	rest_of_crops
16	fruit_temperate	37	roots
17	barley	38	sesame_seed
18	cereals_other	39	soybean
19	millet_small	40	sunflower
20	millet_pearl	41	tobacco
21	wheat	42	vegetable

ANNEX IV: LSMS-ISA crop list

nr	Name	nr	Name	nr	Name	nr	Name
1	fonio	22	Dry_leaves	43	Pepper	64	Unshelled groundnut
2	Acha	23	Garden_egg	44	Pineapple	65	Unshelled maize
3	Agbono	24	Garlic	45	Plantain	66	Unshelled melon
4	Amarante	25	Ginger_peeled	46	Popcorn_maize	67	Walnut
5	Atare	26	Gombo	47	Potato	68	Water_yam
6	Avocado_pear	27	Green_vegetable	48	Pumpkin	69	White_yam
7	Bambara_nut	28	Groundnut peanuts	49	Pumpkin_fruit	70	Yellow_yam
8	Banana	29	Guava	50	Pumpking_leave	71	Zobo
9	Beans cowpeas	30	Kolanut_unshelled	51	Rice	72	Zobo_seed
10	Beeni_seed	31	Letus	52	Rubber	73	Other
11	Carrot	32	Lettuce	53	Seedcotton	74	Peanuts
12	Cashew_fruit	33	Maize	54	Shelled groundnuts	75	Sesame
13	Cassava	34	Mango	55	Shelled_maize	76	Sorrel
14	Chili	35	Melon	56	Shelled_melon	77	Spice(pepper)
15	Cocoa_pod	36	Millet	57	Shelled_rice	78	Squash
16	Coconut	37	Oil_palmtree	58	Sorghum	79	Tomato
17	Cocoyam	38	Onion	59	Sugar_cane	80	Voandzou
18	Coffee	39	Orange	60	Sweet_pepper	81	Wheat
19	Cotton	40	Paddy_rice	61	Sweet_potato	82	Cabbage
20	Cowpeas	41	Pawpaw	62	Tea	83	Jaxatu
21	Cucumber	42	Pear	63	Threeleave_yam	84	Parsley
						85	Watermelon

ANNEX V Cropdata crop list

nr	Name
1	Barley
2	Cassave
3	Chickpea
4	Cotton
5	Cowpea
6	Field bean
7	Jute
8	Kenaf
9	Lentil
10	Maize
11	Millet
12	Mungbean
13	Onion
14	Peas
15	Peanut
16	Pigeonpea
17	Potato
18	Rapeseed
19	Rice
20	Sesame
21	Sorghum
22	Soybean
23	Sugarbeet
24	Sugarcane
25	Sunflower
26	Sweet potato
27	Tobacco
28	Wheat

ANNEX VI Irrigation share per TSU under different scenarios.

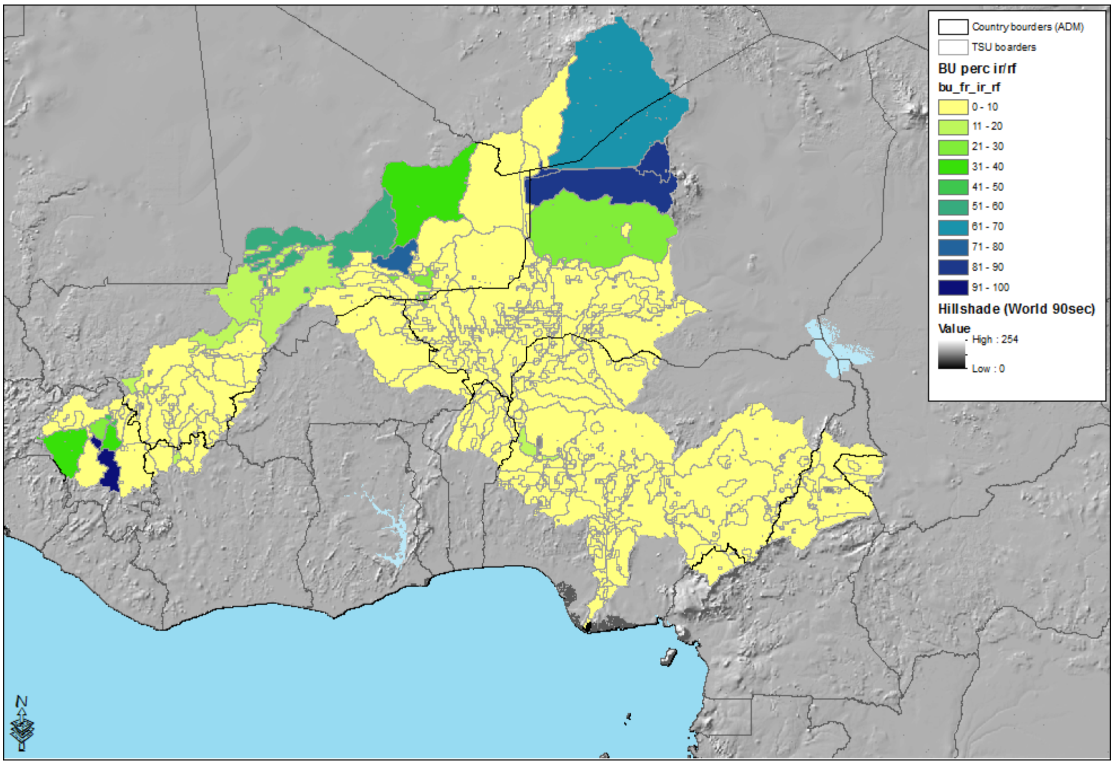

Figure 25: BU irrigation share as fraction of total crop area per TSU.

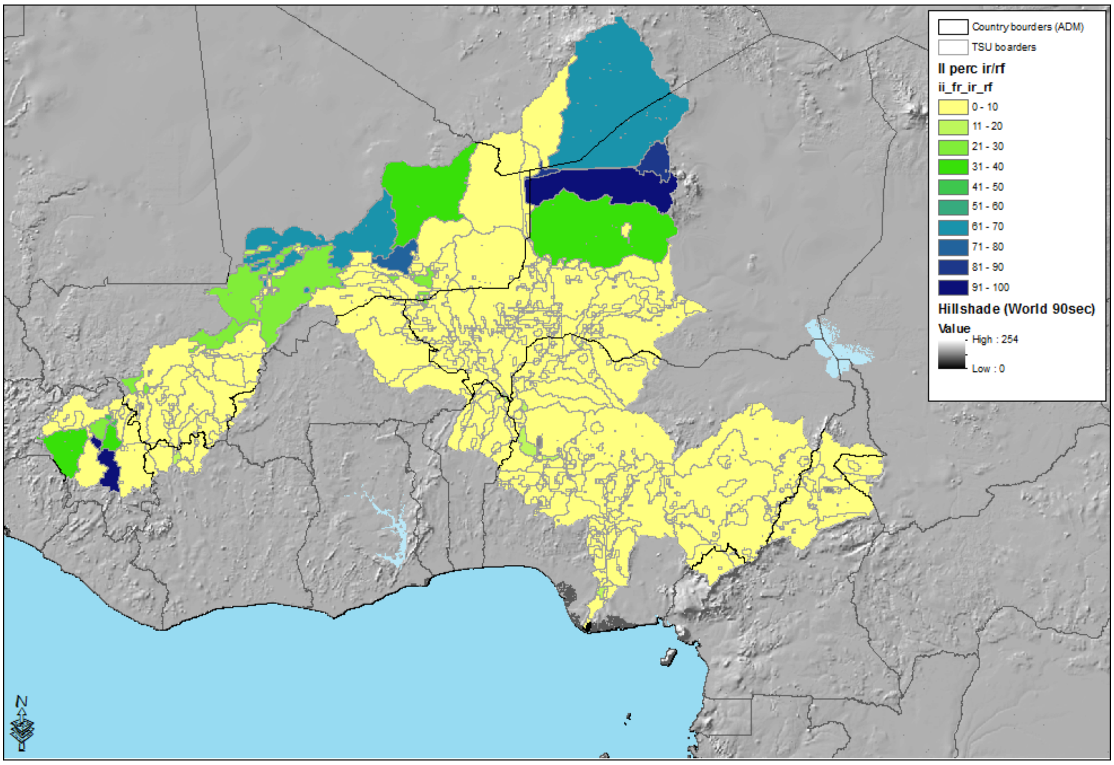

Figure 26: HII irrigation share as fraction of total crop area per TSU.

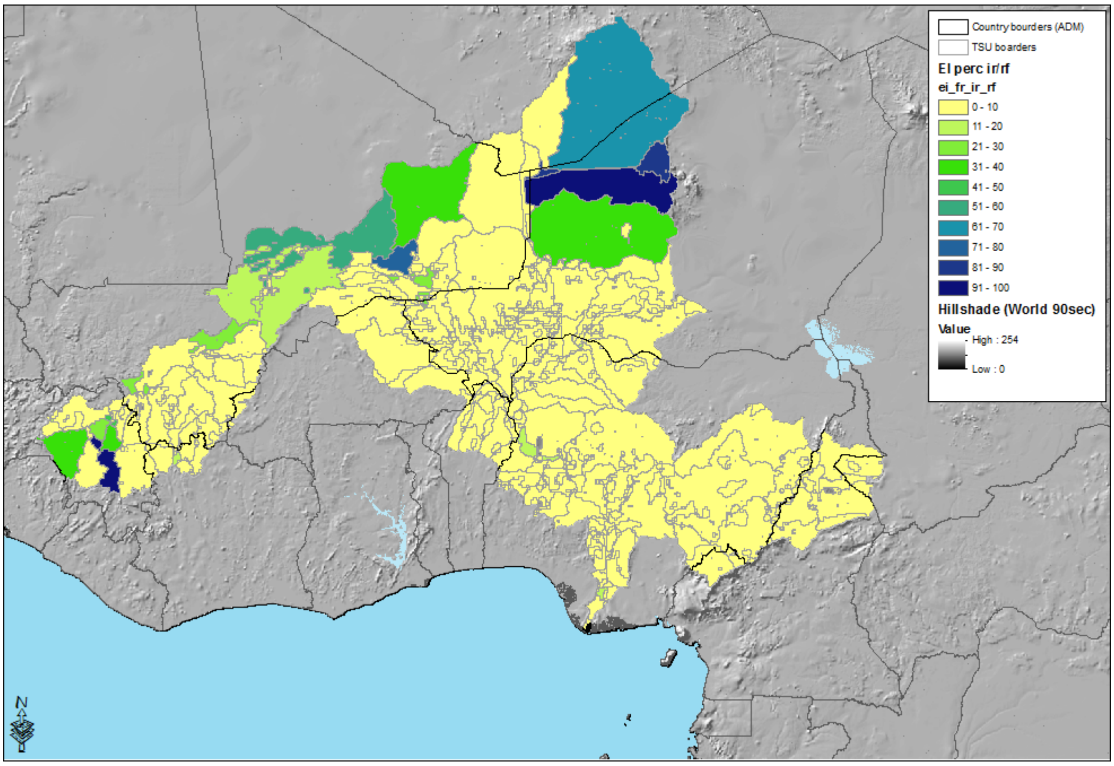

Figure 27: MII irrigation share as fraction of total crop area per TSU.

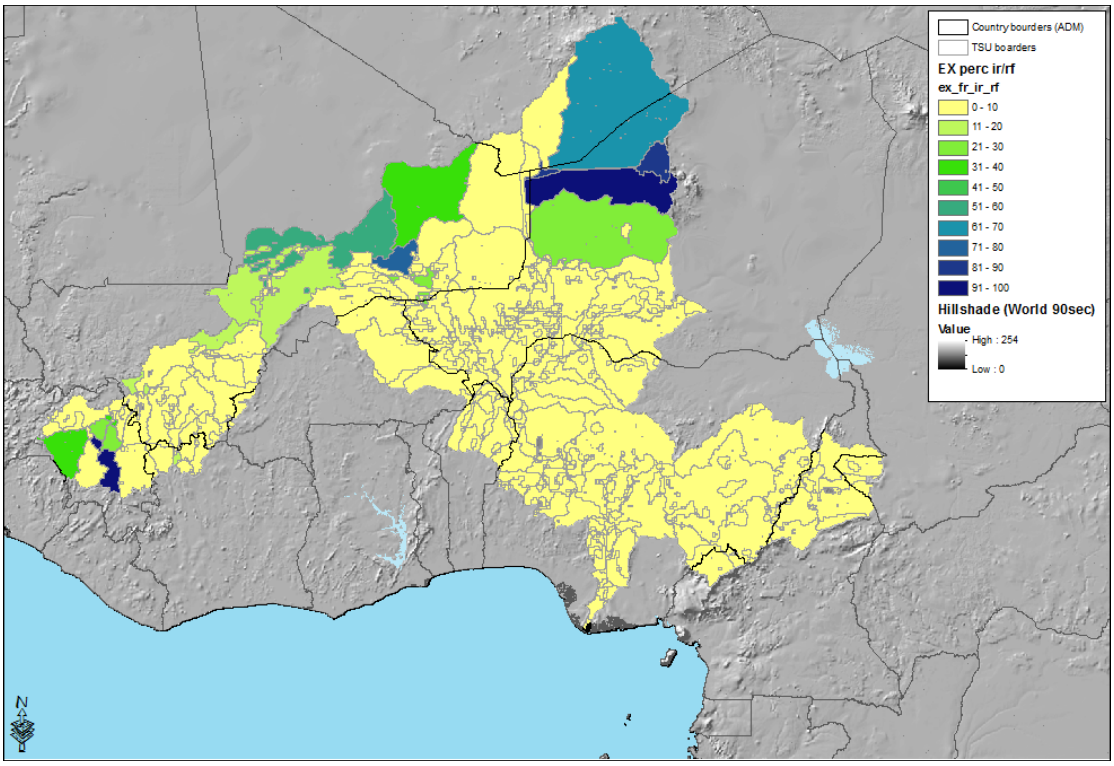

Figure 28: EX irrigation share as fraction of total crop area per TSU.

ANNEX VII: Irrigation requirement in 10^6 m^3 per TSU under different agricultural scenarios.

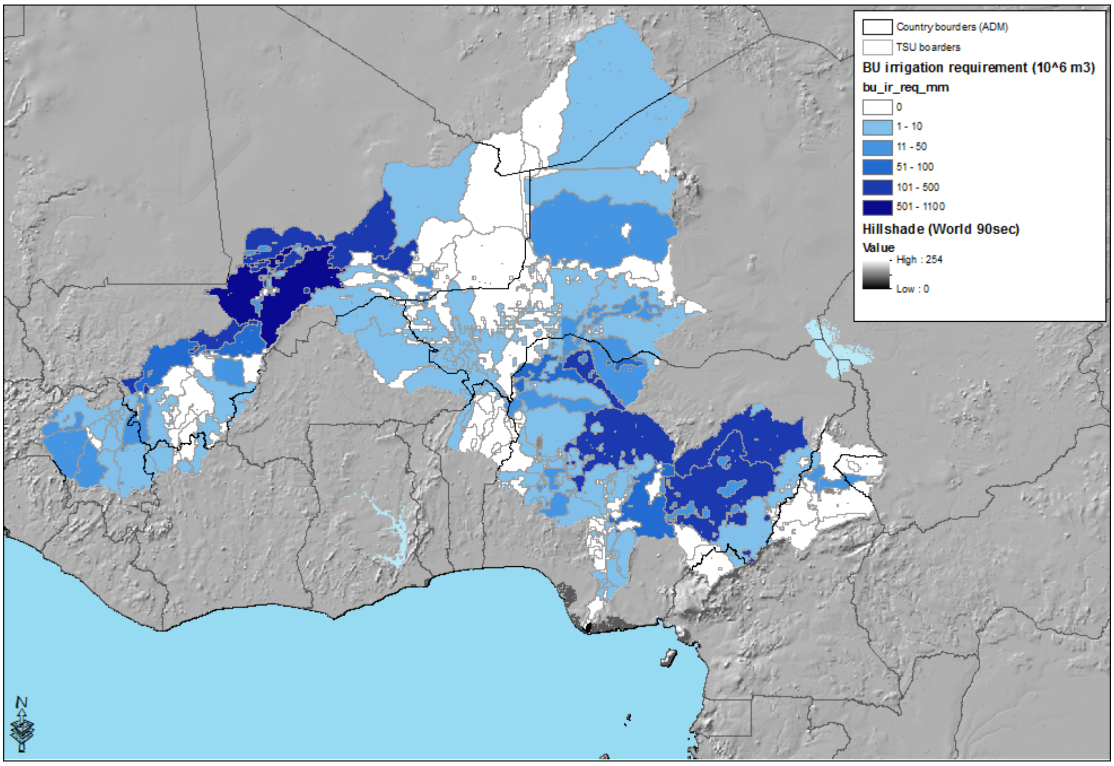

Figure 29: BU irrigation requirement in 10^6 m^3 per TSU.

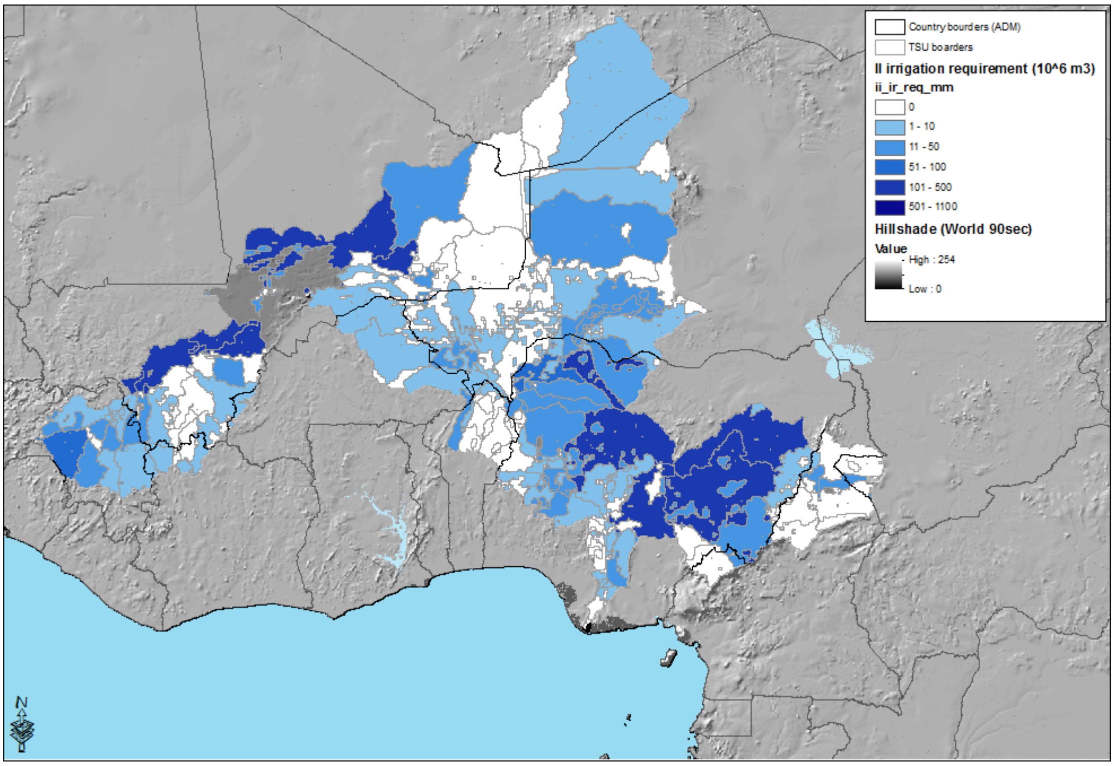

Figure 30: HII irrigation requirement in 10^6 m^3 per TSU.

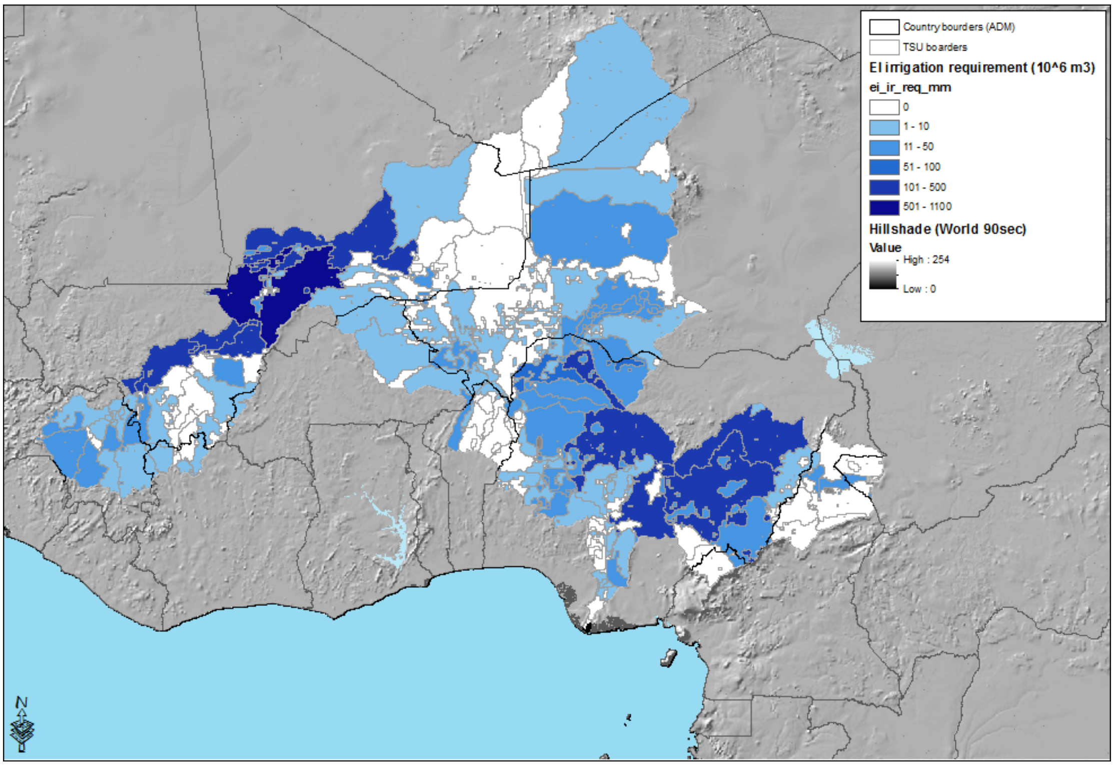

Figure 31: MII irrigation requirement in 10^6 m^3 per TSU.

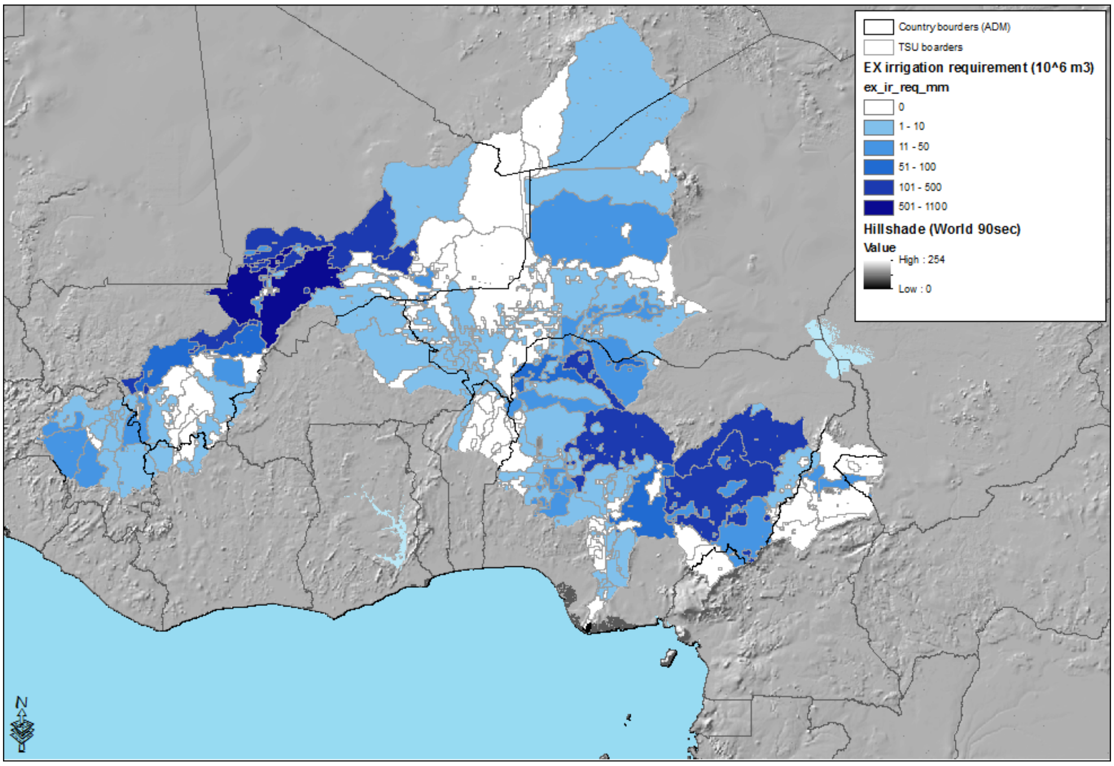

Figure 32: EX irrigation requirement in 10^6 m^3 per TSU.

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