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ZEF-Discussion Papers on
Development Policy No. 223

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Marrit van den Berg

On the use of agricultural system models for exploring technological innovations across scales in Africa: A critical review

PARI

Bonn, July 2016

Reimund P. Rötter, Fanou L. Sehomi, Jukka G. Höhn, Jarkko K. Niemi, and Marrit van den Berg, On the use of agricultural system models for exploring technological innovations across scales in Africa: A critical review, ZEF – Discussion Papers on Development Policy No. 223, Center for Development Research, Bonn, July 2016, pp. 85.

ISSN: 1436-9931

Published by:
Zentrum für Entwicklungsforschung (ZEF)
Center for Development Research
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Acknowledgements

We are very grateful to Joachim von Braun and Detlef Virchow of the Center for Development Research (ZEF) for initiating and supporting this research, e.g. through organizing discussion rounds and commenting on interim results and previous versions of the manuscript. Many thanks go also to the various discussants, Nicolas Gerber, Mekbib Haile, Matthias Kalkuhl, Eike Luedeling, Alisher Mirzabaev, Justice Tambo and Tobias Wünscher (ZEF B) as well as to Frank Ewert, Thomas Gaiser, Eshan Rezaei and Heidi Webber (INRES/University of Bonn) for their comments and support.

Natural Resources Institute Finland (Luke) gratefully acknowledges funding through ZEF with whom it collaborated in this project. ZEF Bonn is the grantee of the German Federal Ministry of Economic Cooperation and Development (BMZ), which supported this research. The paper was developed within the project "Program of Accompanying Research for Agricultural Innovation" (PARI), which is funded by the German Federal Ministry of Economic Cooperation and Development (BMZ).

BMZ

Federal Ministry
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and Development

Abstract

The major challenge of the 21st century is to achieve food security under, roughly, a doubling in food demand by 2050 compared to present, and producing the additional food under marked shifts in climatic risks and with environmentally sound farming practices. Sustainable intensification of agricultural production is required that meets the dual goal of improved environmental sustainability and economic efficiency. *Ex ante* evaluation of technological innovations to support agricultural production and food security taking into account the various future risks can substantially contribute to achieve this. Here we perceive technological innovations as new or improved agro-technologies and –management practices, such as new breeds, integrated soil fertility practices or labour-saving technologies meeting the goals of sustainable intensification.

In this report we present results from three systematic reviews: one on the use of biophysical modelling, the second and third on the use of bio-economic modelling at farm scale and agro-economic modelling at higher aggregation levels, for *ex ante* evaluation of the effects of (**ag**ro-) **Technological Innovations** (**ag-TIs**) on sustainable agriculture and food security indicators. To this end, we searched the SCOPUS database for journal articles published between 1996 and 2015. We considered modelling studies at different spatial scales with particular attention to local to national scale studies for the twelve PARI focal countries in Africa[1]. But we also included studies for all other African countries as well as a few studies at supra-national/continental scale. Both, "quick wins" as well as long term benefits from ag-TIs were of interest. The various ag-TIs were furthermore grouped into four classes: (1) water/soil moisture (2) soil nutrients/conservation (3) crop/cropping system, (4) other ag-TIs or (5) combinations of 1 to 4. For each paper, we tried to identify the primary ag-TI analysed, and if there was equal emphasis to more than one, we classified them as combinations. It should be borne in mind that there is some subjectivity in classifying the papers in this way.

Results. After various steps of refining "search strings", screening on relevance and supplementing databases from additional sources, we found 140 relevant biophysical modelling studies, whereby coverage of sub-regions and ag-TIs varied markedly. Most studies were found for East and West Africa, followed by Southern Africa; hardly anything was found for Northern and Middle Africa[2]. A similar pattern appeared for the integrated agro-economic modelling studies at farm scale, for which we found 40 relevant ones. Agro-economic modelling studies at higher aggregation levels showed a somewhat different pattern – and more generally contained little detail on technological innovations. Regarding the share of different primary agro-technologies explored in the biophysical studies we found 45 on crop

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[1] The 12 countries are, in alphabetic order: Benin, Burkina Faso, Cameroon, Ethiopia, Ghana, Kenya, Malawi, Mali, Nigeria, Togo, Tunisia and Zambia – see, maps, e.g. Fig 7.

[2] See United Nations geoscheme for composition of geographical sub-regions (http://unstats.un.org/unsd/methods/m49/m49regin.htm).

management, 35 on combined agro-technologies, 31 on soil nutrient management and conservation, 23 on water/soil moisture management, and 6 on other technologies. We found similar shares among the various agro-technology groups for the integrated agro-economic modelling studies at farm scale.

Looking at the outcomes from *ex ante* evaluations we found that many studies are (mostly) positive on effects of single and "conventional" ag-Tis. The majority of biophysical studies is performed at "field scale" and focuses on the effects on productivity (sometimes yield stability); many of these studies were performed in climate variability and change /adaptation research context. Most agro-economic modelling studies that look specifically at ex ante evaluations of ag-TIs are performed at farm or regional (sub-national) scales. While the number of biophysically oriented studies has grown exponentially over the considered period 1996-2015, this is not the case for the agro-economic modelling studies.

Looking in more detail at the twelve focal countries of PARI (=Programme of Accompanying Research on Agricultural Innovations)[3] we also find an unbalanced distribution, with most studies found in Kenya, Ethiopia, Mali and Ghana (biophysical modelling studies), and respectively in Kenya and Uganda (agro-economic modelling studies), whereas nothing or little was found for both types of studies in Togo, Zambia and Nigeria.

Very few of the biophysically-oriented studies include other information than effects on crop yields, and there are few studies for both biophysical and agro-economic modelling that comprise multi-scale or higher scale analyses; if multi-scale, there are more studies that scale up from field/farm to regional/sub-national level than from field/farm to nation scale or beyond. There is definitely a need to overcome the lack of meaningful integrated multi-scale modelling along the lines proposed in chapters 5-6 of this report. Moreover, less than half of all integrated /agro-economic modelling studies at farm scale explicitly address risk – another clear shortcoming, which requires attention by the research community.

A more general conclusion is that there is no application yet of true transdisciplinary research approaches in practice. Hence, there is need for participatory, collaborative (cross-sectoral) and combined modelling approaches with adequate stakeholder involvement throughout the research process. In this respect, some lessons might be learned from pioneering work conducted in Asia and Europe.

Keywords: Africa, agricultural system models, agro-economic modelling, biophysical modelling, *ex ante* evaluation, risk, technological innovation, yield variability

JEL codes: C61, C63, C65, C68, D81, O32

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[3] http://www.zef.de/index.php?id=2321&project=43&contact=976&cHash=fa390a6d552a4fb80edd24121687cbbd

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List of Abbreviations

AEM	Agricultural Economic Model
AEZ	Agro-ecological zonation
AfDB	African Development Bank
AgMIP	Agricultural Model Intercomparison and Improvement Project
ag-TIs	(agro-)Technological Innovations
APSIM	Agricultural Production Systems Simulator
ASM	Agricultural System Modelling
BMBF	Bundesministerium für Bildung und Forschung
BMZ	German Ministry for economic cooperation and development
CCAFS	Climate Change, Agriculture and Food Security
CGE	General Equilibrium Models
CGIAR	Consortium of International Agricultural Research Centers
CMIP	Coupled Model Intercomparison Project
CropM	Crop Modelling
CRV	Central Rift Valley
DSSAT	Decision Support System for Agrotechnology Transfer
EPIC	Erosion-Productivity Impact Calculator
EU	European Union
FAO	Food and Agriculture Organization of the United Nations
FS	Farming System
FYM	Farm Yard Manure
GAEZ-LPG	Global Agro-Ecological Zone - Length of Growing Period
GCM	Global Climate Model
GDP	Gross Domestic Product
GEnS	Global Environmental Stratification
GIC	Green Innovation Center
GLI	Global Land Initiative
GYGA-ED	Global Yield Gap Atlas - Extrapolation Domain
HCAEZ	HarvestChoice Agro-ecological zonation
HEI	High-end impact
IBID	Institute for Business and Industry Development
ICRAF	The World Agroforestry Centre
IFPRI	International Food Policy Research Institute
ILRI	International Livestock Research Institute
INRA	National Agricultural Research Institute (of France)
IPCC	Intergovernmental Panel on Climate Change
LPJml	Lund-Potsdam-Jena managed Land
Luke	Natural Resources Institute Finland (Luonnonvarakeskus)
MACSUR	Modelling European Agriculture with Climate Change for Food Security

MAS	Multi Agent System
MSA	Multi-Scenario Agreement
MI	Median impact
NL	Netherlands
OECD	Organisation for Economic Cooperation and Development
PARI	Programme of Accompanying Research on Agricultural Innovations
PIK	Potsdam Institute for Climate Impact Research
RAPs	Representative Agricultural Pathways
SAGE	Center for Sustainability and the Global Environment
SEAMLESS	System for Environmental and Agricultural Modelling Linking European Science and Society
SPAM	Spatial Production Allocation Model
SRES	Special Report on Emissions Scenarios
SSA	Sub-Saharan Africa
SUCROS	Simple and Universal Crop growth Simulator
SysNet	Systems Research Network for Ecoregional Land Use Planning
TI	Technology innovation
UN	United Nations
UNDP	United Nations Development Programme
WASCAL	West African Science Service Center on Climate Change and Adapted Land Use
WGII	Working Group II
WU	Wageningen University
YG	Yield Gap
ZEF	Center for Development Research

1 Introduction

1.1 Overall goal and key questions

One of the major challenges of the 21st century is to achieve food security under marked shifts in climatic risks and roughly a doubling in food demand by 2050 compared to present. Increased frequency and severity of extreme events are threatening future harvests, especially challenging agricultural production systems in African regions that are already food insecure (Knox et al., 2012; Wheeler & von Braun, 2013; Thomas & Rosegrant, 2015). Sustainable intensification is required that meets the dual goal of improved environmental sustainability and economic efficiency (Godfray et al., 2010; Godfray, 2015). Ex ante evaluation of technological innovations to support agricultural production and food security taking into account climate-induced risks is of major concern.

The declared overall goal of this study is to critically review the use of agricultural system modelling (ASM) over the period 1996 to 2015 for ex ante evaluation of technological innovations in Africa; in particular, to assess capabilities, gaps and the potential of ASM to inform decisions on investments in developing agro-technologies and supportive policies.

Technological innovation (TI) is the process through which new (or improved) technologies are developed and brought into widespread use. Here we consider (agro-) technological innovations (ag-TIs) as new or improved agro-technologies such as irrigation and soil water management practices, use of new and diverse breeds, integrated soil fertility practices or labour-saving technologies meeting the goals of sustainable intensification.

Ex-ante analysis of agro-technologies is needed as many of these technologies are not yet in place and it would be too costly and time-consuming to test all of them empirically under the various field conditions and socio-economic settings. Agricultural System Models (ASMs) are required for ex-ante analysis of ag-TIs since the latter have complex demands on physical and institutional resources (see, e.g. Graef et al., 2014); moreover, their long-term effectiveness will not just depend on their technical feasibility or effectiveness but also on their profitability at farm-level and economy-wide (see, e.g. Graef et al., 2014). Bio-economic modelling can take some of these factors into account. Ex ante evaluation of ag-Tis is important and a pre-requisite if our aim is to look beyond current policy and other (e.g. institutional, technological) constraints. It is the particular strength and capability of ASMs to facilitate such future-oriented scenario analyses (see, e.g. van Ittersum et al., 2004; Jones et al., 2015; van Wijk et al., 2014).

For some time already, agricultural systems science has considered integrated agricultural system modelling for ex-ante evaluation of agro-technologies as a crucial research field – for instance, in support of exploring alternative agricultural development scenarios (de Wit et al., 1988) - and as an important building block of generating information to feed the development cycle of policies on land use and natural resource management (Van Ittersum et al., 2004; König et al., 2013).

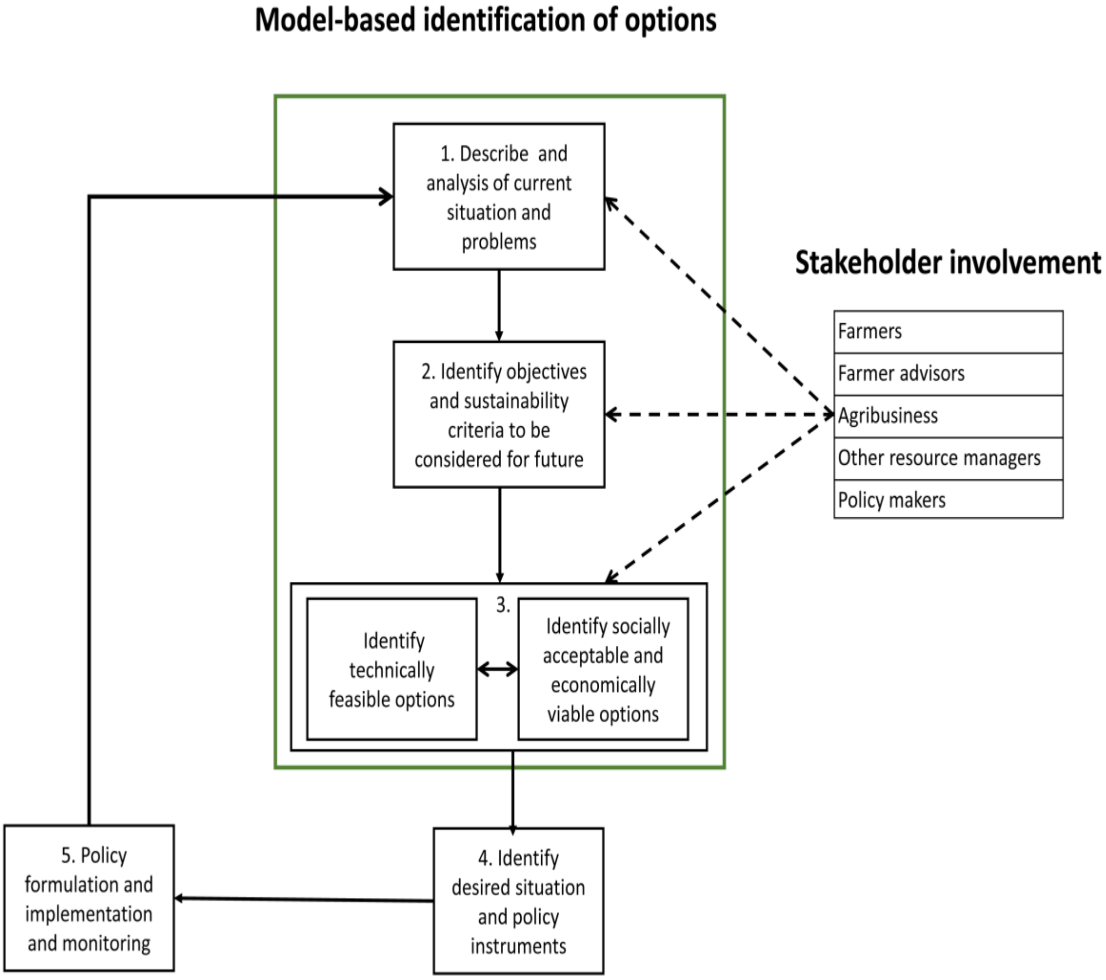


Figure 1: Part of the development cycle of policies for natural resource management and land use (steps 1-3 in the green box) supported by agricultural system modelling studies and stakeholder interaction

Source: modified from van Ittersum et al., 2004

To identify technically feasible options, first of all, biophysical modelling (step 3, left hand) is needed as indicated in Fig.1. Integrated agro-economic modelling (step 3, right hand) can then deliver valuable inputs for identifying technically feasible as well as socially acceptable and economically viable options in close interaction with (key) stakeholders. Modelling frameworks for such analyses have been developed, among others, by SysNet in Asia (Van Ittersum et al., 2004; Rötter et al., 2005; Laborte et al., 2007). These frameworks, however, were not yet designed for taking into account the various dimensions of climatic change. Furthermore, to our knowledge, no such elaborated frameworks for model-aided transdisciplinary research and multi-scale analyses in Africa do exist; yet, first steps have been taken in that direction (e.g. König et al., 2013) and various useful building blocks have become available for a range of farming systems (see, Sections 3 and 4 of this report). More recently, some prototype modelling frameworks have emerged (e.g. in the framework of CCAFS and AgMIP) (e.g. Herrero et al., 2014; Kihara et al., 2015) that appear promising for future applications in Africa.

Following various discussion rounds at ZEF during spring 2015, **four key questions** were formulated:

1. What type and how many agricultural system modelling (ASM) studies on ex-ante impact assessment of technological innovations (ag-TIs) have been performed?
2. What are the outcomes, i.e. the magnitude and type of effects of ag-TIs on sustainability/food security indicators (income, productivity, environmental impact, the various food security dimensions)?
3. What are the gaps - and can they be bridged with respect to target areas and agro-technologies considered as well as weaknesses regarding the methodology?
4. And more generally: What role could ASM play in supporting future decisions on ag-TIs – and what recommendation can be given regarding their use?

1.2 Context: the overarching scientific program on Green Innovation Centers

While globally food supplies currently exceed food demand, there are at the same time still more than 800 million people undernourished and two billions suffer from chronic malnutrition. The problem of too many people being deprived of sufficient, safe and healthy food is difficult to tackle as the Earth's population continues to grow for the next 1-2 generations. It has been projected that the population of the earth will reach approximately 9-10 billion people by 2050. This population growth is expected to occur mainly in Africa and South Asia (Rosegrant et al., 2013).

Hunger primarily results from poverty and the majority of those who are starving from hunger are small-scale farmers (Wheeler and von Braun, 2013). Regional food insecurity is further caused by a considerable proportion of food being spoiled because food storage, processing and trade are not coordinated. Furthermore, increased frequency and severity of extreme weather events threaten future harvests, and this will especially challenge agricultural production systems in African regions that are already food insecure. As reported, among others, by Müller et al. (2014), Africa has the largest share of poor and undernourished people and is projected to have the largest population growth rates (Lutz & Samir, 2010), as well as above-average climate change over the 21st century (Christensen et al., 2007; IPCC, 2014).

It has been widely recognized that sustainable intensification is needed for Africa's agriculture and food systems for meeting the challenge of increased demand, improved environmental sustainability and economic efficiency. In the face of growing food demand, declining natural resources and climate change, technological (and institutional) innovations, locally adapted, are direly needed for such sustainable intensification.

In response to this challenge, the German Government supports the improvement of food and nutrition security and sustainable agricultural value chains in Africa through its new program "Green Innovation Centers - GICs" in 12 African countries (Benin, Burkina Faso, Cameroon, Ethiopia, Ghana, Kenya, Malawi, Mali, Nigeria, Togo, Tunisia and Zambia). The GICs form the core of a comprehensive approach to promote the African agri-food sector. These 12 GICs in Africa (and an additional one in India) are supported by the independent Program of Accompanying Research for Agricultural Innovation (PARI) (http://research4agrinnovation.org/), led by the Center for Development Research, ZEF, in collaboration with African and German partners and funded by the German Federal Ministry for Economic Cooperation and Development (BMZ). One of PARI's tasks is to conduct accompanying research with future oriented impact analyses of potential innovations, including the development of a methodology and concept for strategic analysis and visioning and modeling the direct and indirect impacts of potential promising innovations.

One of the starting points in this area of PARI's work is the question what role agricultural system models have played generally and for Africa in particular in ex ante evaluation of technological innovations across different scales. This has triggered the critical review documented in this report.

1.3 Need for a comprehensive methodology for assessing multiple risks to crop production

In the 5th Assessment report of the IPCC, contribution of Working Group II (Field et al., 2014), a risk assessment framework is presented as the core concept, in which risks (and opportunities) are the resultant from the interaction of climate–related hazards with the vulnerability and exposure of natural and human systems. Risks can be reduced, e.g. by adaptation and mitigation actions (see Fig S1).

When it comes to risks to food production, their shifts under a changing climate, and related uncertainties that matter to farmers, one may state a bit provocatively that not changes in mean yield, but shifts in yield variability really matters – as is further elaborated hereunder.

In recent years we could observe that yield variances for major food crops in important agricultural areas are on the rise, such as for maize in Eastern Africa or wheat in Europe (Iizumi and Ramankutty, 2016; Trnka et al., 2014).

Figure 2a indicates that higher input use results in high yields in most years, but also in higher losses (in terms of inputs purchased) in years with climate-induced crop failures. Figures 2b and 2c further illustrate this by contrasting the low mean yield and yield variance for unfertilized plots vs the high mean yield and yield for plots with high applications of inorganic fertilizers and manure. This schematically illustrates that the implications of a doubling of climate-induced risk of crop failure are higher for high-input agriculture: higher forgone yields but more importantly higher monetary losses due to spending on external inputs.

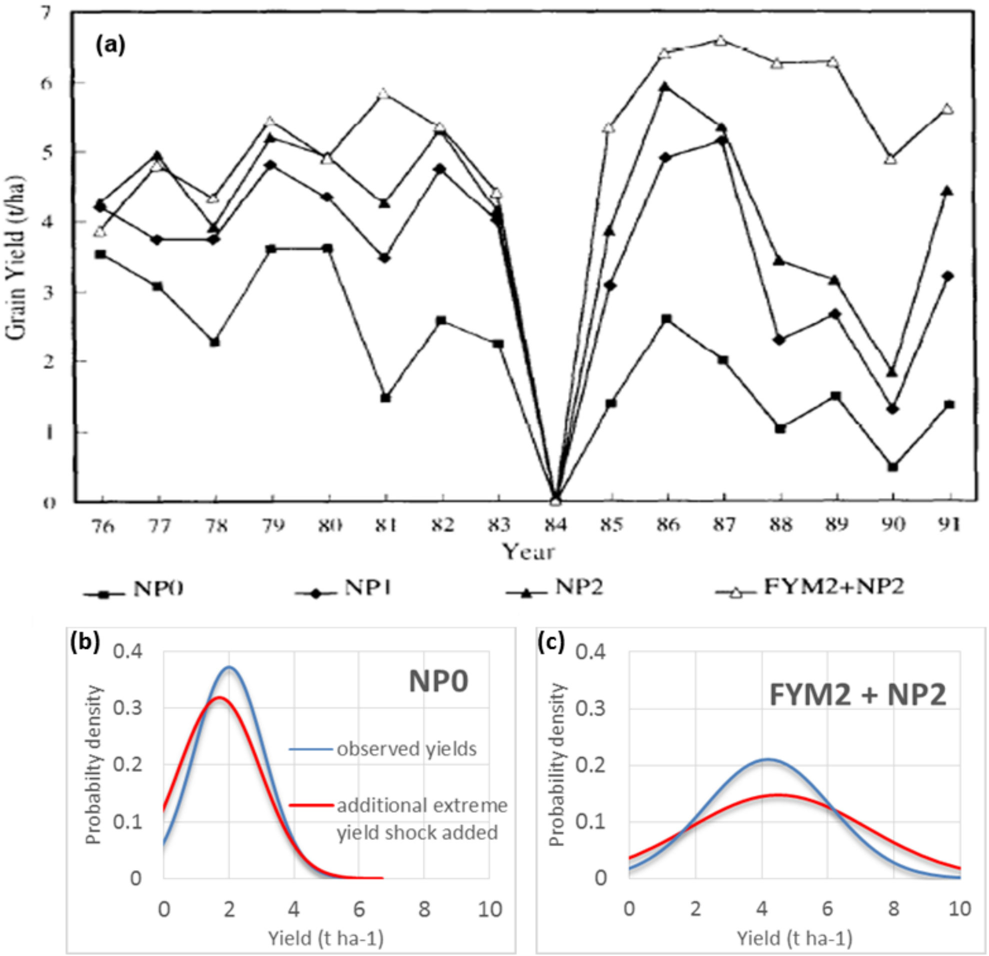


Figure 2: Maize yield series and probability density functions fitted to these yields

Note: (a) Maize yield series at Nairobi for different soil fertility management treatments (1976-91) (TMTs NP0, NP1, NP2 are N0P0, N60P26 and N120P53, respectively; FYM2 is 10 t ha-1), (b) and (c) Probability density functions fitted to these yield series for two treatments (NP0 and FYM2+NP2) (blue curves) and pdfs for these treatments with hypothetically doubled yield shocks by rainfall deficit (red curves).

Sources: Figure 2 (a) is reprinted from Agricultural Systems 53(1), Rötter & van Keulen, Variations in yield response to fertilizer application in the tropics: II. Risks and opportunities for smallholders cultivating maize on Kenya's arable land, page 79, Copyright (1997), with permission from Elsevier.

Often, model-based risk analyses only take a single or a few adverse events (such as drought, flooding or heat) into account. Given the limitations of different approaches, e.g. the limitation of most crop simulation models to sufficiently capture effects of extreme events (Rötter et al., 2011; Wheeler & von Braun, 2013; Porter et al., 2014; Ewert et al., 2015) and that of agro-climatic indicator approaches to quantify the effects of adverse weather on crop yields (Trnka et al., 2011; Rötter et al., 2013), a well-tested methodology for assessing multiple risks to crop production (see also, Trnka et al., 2014) is still lacking (Wheeler, 2015). Such deficiency is not restricted to Africa but is a more general problem and requires promotion of international efforts are (e.g. through AgMIP and MACSUR) that combine the strengths of different biophysical and agro-economic modelling approaches for establishing an appropriate methodology for multiple risk assessment (Rötter & Höhn, 2015; Ewert et al., 2015). Such methodology should clearly go beyond quantifying the biophysical effects of extreme or adverse weather on crop production but also assess their various socio-economic consequences.

1.4 Reader's guide

In chapter 2, we present various stratifications on agro-ecological conditions, an overview on farming systems and an outlook on socio-economic conditions in Africa. Chapter 3 constitutes the core of this report, and is divided into an introduction on the scope and need for ag-TIs - with an overview of recent Africa-wide modelling studies, and the presentation of detailed results from the three systematic reviews. In chapter 4 we present generalized findings from the three reviews. Chapter 5 presents a possible generic modelling framework for Africa and selected case studies which employ promising modelling approaches relevant (at least to some degree) to the planned Green Innovation Centers in the 12 African focal countries. In chapter 6, finally, we present some conclusions and an outlook on potential future work.

2 Agro-ecological and socio-economic conditions in Africa

Agro-ecological zones (AEZ) often serve as a frame for supporting the generalization and up-scaling of modelling results from farm level and other local studies on technological innovations to higher aggregation levels (sub-national/regional, national and beyond) (e.g. Van Wart et al., 2013b). To be able to extrapolate site-specific (point) analysis of agricultural system performance to larger areas, insight in the distribution of agro-ecological conditions and farming systems throughout Africa is needed see, e.g. Harvestchoice 2010; Dixon et al., 2014. Stratified sampling and spatial analysis has been employed in particular in data scarce regions such as in Africa (Thornton et al., 2011; Van Wart et al., 2013a; Van Bussel et al., 2015). Furthermore, for future-oriented studies such as ex ante evaluation of technologies, it is required to make projections regarding system boundaries, i.e. future availability of agro-ecological and socio-economic resources. To this end we present different agro-ecological zonations (section 2.1), the distribution of generalized farming systems (section 2.2), an overview of future climate projections and climate risks (section 2.3), and a brief outlook on socio-economic resource availability (section 2.4) in Africa.

2.1 Agro-ecological zonations

Increasing agricultural production in a sustainable manner requires profound knowledge about the constraints which currently limit the productivity of agricultural systems. Agro-ecological zones (AEZs) can provide such information. Based on a standardized framework they capture environmental limitations and potentials of land resources which are broadly set by climate, soil and terrain characteristics and delineate geographic regions sharing similar conditions. Such knowledge can support the development of land-use policies, the setting of agricultural research priorities, and the development and transfer of agro-system specific technological innovations.

Various AEZ schemes have been developed since the initiatives of FAO in the late 1970s (FAO, 1978) (see Table 1) and successfully applied for assessing land suitability and potential productivity (FAO, 1978), extrapolating regional knowledge on crop management practices and innovative technologies to locations sharing similar production conditions (Seppelt, 2000), and analyzing climate change impacts on land suitability and agricultural production (Fischer et al., 2005; Bonfante and Bouma, 2015).

Table 1: Agro-ecological zonation (AEZ) schemes

AEZ scheme	Number of zones	Coverage	Resolution*	Variables considered, methodology	Reference
FAO	14	Global	n.s.	Mean growing period temperature and length of growing period determined by annual precipitation, potential evapotranspiration and the time required to evapotranspire 100 mm of water from the soil profile	FAO (1978)
GAEZ-LGP	16	Global	10 arcmin	Temperature, precipitation potential evapo-transpiration and soil characteristics are used to calculate length of growing season	Fischer et al. (2012)
HCAEZ	21	Global	10 arcmin	Monthly mean temperature, elevation and length of growing period are used to define thermal regimes and temperature seasonality	Wood et al. (2010)
SAGE	100	Global	5 arcmin	Growing degree days (GDD; ∑Tmean–crop-specific base temperature) and soil moisture index (actual evapotranspiration divided by potential evapotranspiration)	Licker et al. (2010)
GLI	25	Global	n.s.	Harvested area of target crop, crop-specific GDD and soil moisture index (actual evapotranspiration divided by potential evapotranspiration)	Müller et al. (2012)
GEnS	115	Global	30 arcsec	GDD with base temperature of 0 °C, aridity index, evapotranspiration seasonality, temperature seasonality used in iso-cluster analysis to "cluster" grid-cells into zones of similarity	Metzger et al. (2013)
GYGA-ED	300 (265 zones with major crop cultivation)	Global	5 arcmin	GDD with base temperature of 0°C, temperature seasonality (quantified as standard deviation of monthly average temperatures), aridity index (annual total precipitation divided by annual total potential evapotranspiration)	van Wart et al. (2013b)
Jätzold and Kutsch	56	Continental with a case study for Kenya	n.s.	Annual mean temperature, aridity/humidity index (effective Precipitation /potential Evapotranspiration (Pe/Etp)), length of growing period based on probabilistic information on seasonal precipitation and differentiated soil moisture storage	Jätzold and Kutsch (1982)

While zonation schemes often differ in terms of resolution and coverage, they most commonly combine temperature zones and soil water availability or drought indices to delineate similar zones. Thermal zones may be defined based on annual mean temperature (Jätzold and Kutsch, 1982 -and updates of 2012)), monthly mean temperature (HCAEZ) or growing degree days either calculated by using crop-specific (SAGE, GLI schemes) or non-crop-specific base temperatures (GEnS, GYGA-ED schemes). Soil water availability indices which aim at quantifying the degree of water limitation to crop production are either calculated as the ratio of annual precipitation to potential evapotranspiration (GEnS, GYGA-ED) or, by taking the field water balance (soil water supply - crop water demand) explicitly into account; this is sometimes approximated by the ratio actual evapotranspiration to potential evapotranspiration (Jätzold and Kutsch, 1982; GAEZ-LPG, HCAEZ). This approach is also applied to determine the effective length of growing period, i.e. when crop growth is possible thermally and without severe water limitations.

An example of the agro-ecological zonation of Africa - based on the global HarvestChoice AEZ scheme (HCAEZ) – can be found in the supplemental information (see, Figure S2).

2.2 Farming systems

Defining African farming systems (FS) allows having a representation of the population of existing farms with similar agro-ecological and socio-economics characteristics, livelihood patterns, constraints and investment opportunities (Garrity et al., 2012). Usually farmers living in the same farming system have similar farming practices, livelihood strategies, development pathways, infrastructure and policy needs (Sebastian, 2014).

The classification of African agriculture in farming systems has been undertaken earlier by Dixon et al. (2001) and has recently been updated by Garrity et al. (2012). For PARI, knowing the different farming systems within each of the target countries is useful for prioritizing and choosing appropriate agricultural innovations for sustainable agricultural production growth and poverty reduction in Africa.

In total, 16 generalized farming systems types can be found in Africa. Five of these farming systems represent most of the rural poor in Sub-Saharan Africa (SSA). These are the maize mixed, agropastoral, highland perennial, root and tuber crop, cereal-root mixed (Sebastian, 2014). Except for Tunisia, each of the PARI country covers at least two of the five main farming systems. Figure 3 presents the main farming systems found in Africa as a whole.

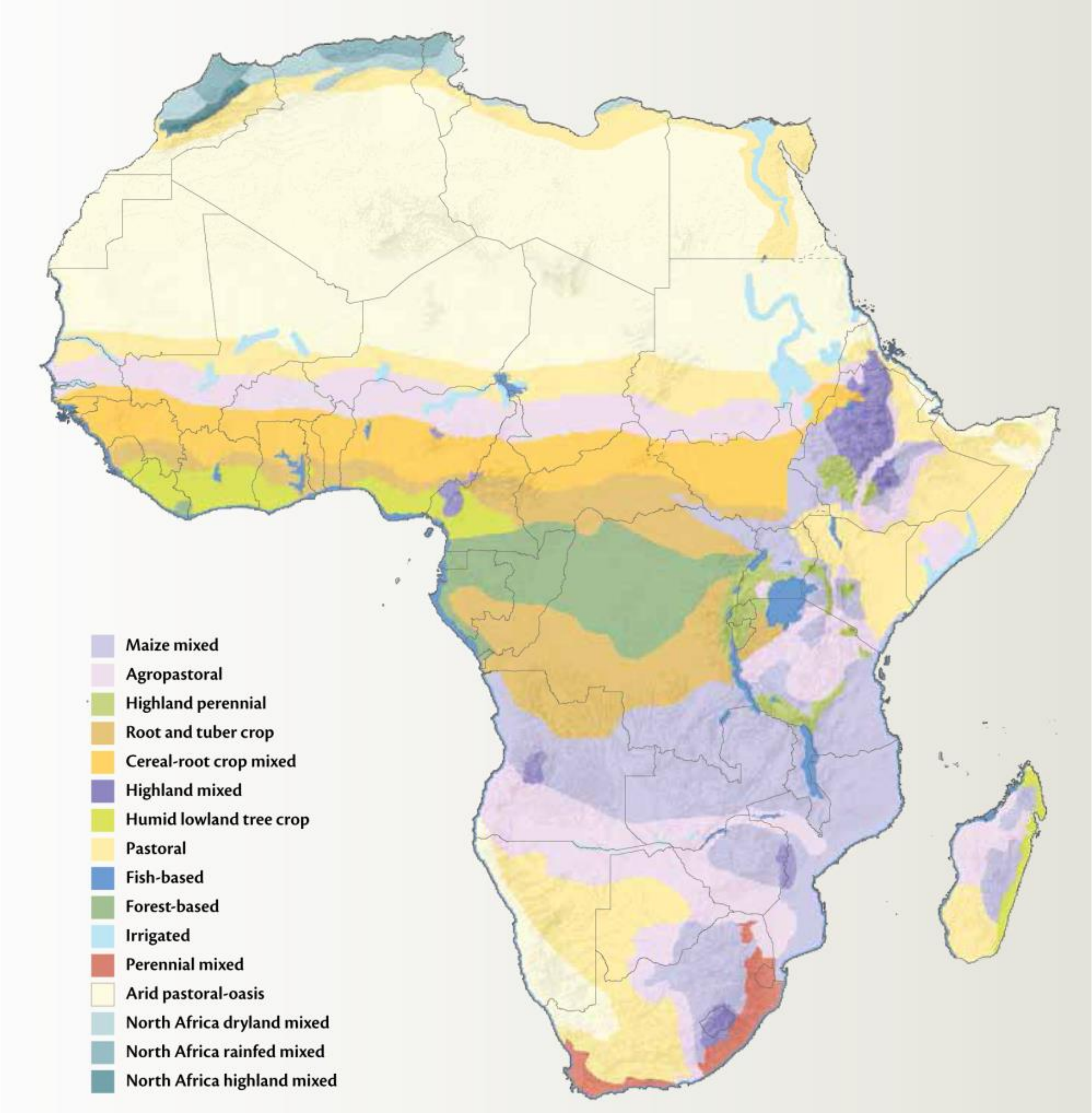


Figure 3: Farming systems of Africa

Source: based on Dixon et al. (2014)

2.3 Future climate projections and climate risks to food production

Agricultural systems are inherently vulnerable to climate variability (Müller et al., 2011), and climate change is expected to increase this vulnerability (Rosenzweig et al., 2014; Thornton et al., 2011). Various global and regional studies warn that progressive climate change is expected to negatively affect crop productivity in most parts of the world (Wheeler and von Braun, 2013) and particularly in Sub-Saharan Africa (Christensen et al., 2007; Cairns et al. 2013; Cooper and Coe, 2011; Müller et al., 2011; Waha et al., 2012). Several of the focal countries of this study (e.g. Ethiopia, Kenya, Mali, Benin, Burkina Faso) are among the most vulnerable countries in sub-Saharan Africa due to their great reliance on climate sensitive sectors, particularly agriculture (Thornton et al., 2006). More generally, the semi-arid to arid climatic zones in East, West and Southern Africa have been traditionally been known to represent high climate risk prone agricultural areas that are frequently suffering from drought and hunger (Rötter & van Keulen, 1997; Thornton et al., 2006, 2011; Hellmuth et al., 2007; Cooper and Coe, 2011).

A recent comprehensive study by IFPRI deals with climate change impacts on food production in Africa. There is a summary of the study by Thomas & Rosegrant (2015) and detailed results for different parts of Africa reported by Hachigonta et al. (2013), Jalloh et al., (2013) and Waithaka et al., 2013, respectively (see also, subsection 3.1.2). For that study, climate projections for mid-century (2050s) from four GCMs (global climate models) have been down-scaled to 5 arc-minute grids (roughly 9 x 9 km at the equator) and utilized for simulating expected yield changes for various crops in the main agricultural regions of Africa. These climate projections only partially cover the full range of projected changes as simulated by different GCMs as simulated by (Weedon et al., 2014) but were rather chosen by their accessibility/ availability.

Yet, even when using the same emission scenario (here: SRES A1B) the differences in the projected changes in temperature and precipitation among the four models selected by IFPRI are still considerable – both in spatial patterns and magnitude of the changes. This is particularly true for projected changes in precipitation (Thomas & Rosegrant, 2015, p. 154-155) with biggest discrepancies among the different models for Eastern Africa. This is also illustrated in the study by Kassie et al. (2015) on climate change impacts on maize production in the Central Rift Valley of Ethiopia, whereby the huge discrepancies among models (see, Fig. S3) may be partly due to insufficient understanding of basic processes in the climate system for the Eastern African region (e.g. Funk et al., 2008).

Here a brief summary of regional and inter-model differences is given. For more details the interested reader is referred to specific research articles on climate projections for Africa (Christensen et al., 2007; Webber et al., 2014; Weedon et al., 2014). Regarding projections of precipitation there is no real consensus among models. For instance, for changes in West Africa's mean annual precipitation there are discrepancies in predicted changes between an 18% decrease to an increase of 16% for the same emissions scenario and period. Ranges of similar order of magnitude and even larger are found for sub-regions in Eastern Africa. The lack of agreement between GCMs is related to their coarse resolution as well as the complex biophysical factors that determine atmospheric circulation processes and associated precipitation regimes in West and East Africa (Christensen et al., 2007; Funk et al., 2008).

2.4 A brief socio-economic outlook

Africa is renewing with a steady increase in economic growth, but with a pronounced geographical disparity. After a decline in 2013, Africa's gross domestic product (GDP) is expected to experience a steady increase by 4.5% in 2015 and 5% in 2016 (AfDB/OECD/UNDP

2015). In 2014, Africa’s annual GDP growth (3.9%) was one percentage point lower than predicted because of slow recovery of the world economy and severe domestic political and health issues in certain African countries (ibid). However it is expected that Africa will recover the rate of economic growth (above 6%) that was achieved prior to the 2008-2009 world economic crisis (ibid). Africa’s economic growth is currently driven by agriculture, extractive industries, construction and services coupled with a rise in private consumption and infrastructure investment (ibid).

Western Africa is the fastest growing African region. In 2014, despite the Ebola crisis and the rise of international terrorism, West Africa achieved a relatively high growth rate of 6% (AfDB/OECD/UNDP 2015). Nigeria –the leading economy in this region, grew by 6.3%. This growth resulted mainly from non-oil sectors (ibid), underpinning the critical role of agriculture in sustaining economic growth. On the contrary, the slow growth of the Republic of South Africa in 2014 (1.5%) has induced a relatively lower economic growth (3%) of the Southern African economy (ibid).

Increased private consumption in Africa is partly related to considerable demographic changes and urbanization. According to United Nations (2015), the current African population (1.2 billion) will have more than doubled by 2050 (2.5 billions) and is expected to have more than tripled around 2100 (4.4 billion). This means, while currently Africans only make up less than one sixth of the world population, their share will have increased to more than one fourth by mid-century. This, despite the fact that Africa’s rate of population growth is declining, after the recent peak rate of population growth (2.5 % per year). Still, from now up to 2050, one in every two new born in the world will be African (ibid), and it is expected that in the next 35 years, 1.3 billion people will be added to the African population. The population is likely to increase in several countries targeted by the current Green Innovation Centers project. Nigeria and Ethiopia are among the nine countries where most of the population increase will take place between now and 2050 (United Nations, 2015). Malawi, Mali and Zambia, which figure in the UN list of least developed countries, will have their population tripling by 2100 (ibid).

Africa will be the youngest continent in the world with one of the fastest urbanization rates (World Bank, 2015). For the next decade, 11 million young people will enter the African job market each year (ibid). This constitutes serious socio-economic challenges for African governments, and the agricultural sector should contribute to absorbing this rising workforce. The population increase induces rapid urbanization in the continent. According to the World Bank overview on Africa, the continent has the world’s fastest urbanization rate. One in two Africans will live in urban areas by 2040, representing 450 million more Africans than today. Despite the increase in urbanization rate, agriculture currently employs 60 % of African workforce. Most of them currently live in rural areas and are among the continent’s poorest and most vulnerable populations.

Climate change is affecting the livelihood of Africa's rural population. Changes in temperature and rainfall patterns are prominent across Africa (Christensen et al., 2007; IPCC, 2014). The severity of natural disasters such as drought and flood has been noticeable, and often being connected to the El Nino Southern Oscillation (ENSO) phenomenon affecting large parts of Eastern and Southern Africa, respectively (Cai et al., 2014; Field et al., 2014). If nothing is done to tackle the impact of climate change with increased frequency of adverse weather events, internal migration to urban areas in search of limited urban jobs is likely to increase, with the risk of raising the amount of urban poor in the next 40 years. Investing in climate-change adaptation techniques and disaster risk management is therefore very crucial to control urbanization rates in Africa.

The economic and demographic growth experienced by Africa hides poverty and food insecurity issues that agriculture can contribute to solve. Africa has the largest share of poor and undernourished people (Lutz & Samir, 2010; Müller et al., 2014). To address this issue, agricultural productivity must be improved via access to improved technologies, rural financial services, and better access to input and output markets. Investment in agriculture should increase, especially in water management via the adoption of modern irrigation technologies and climate-smart agricultural practices (see, e.g. Cassman & Grassini, 2013). Access to improved agricultural technologies is certainly a strategy to achieve the adopted sustainable development goals (SDGs) related to poverty, hunger, food security, nutrition and sustainable agriculture (UN, 2015b).

3 Capabilities and limitations of agricultural system models

Agricultural systems models cover a wide range of scales and methods, including process-based crop simulation, statistical crop yield models, economic optimisation and agro-economic models at household, regional and supra-national scales. Such models are in principle capable of quantifying important environmental and economic performance indicators of alternative technologies and their variability under current and future conditions. As different types of models have different capabilities, an integrated assessment of TIs would ideally be based on a multi-scale and multi-disciplinary framework comprising several models, such as the framework of Reidsma et al. (2015) (see, Figure S4), who applied this to assess the agricultural impacts of changes in climate, agro-technologies and markets at EU and regional level.

Because such studies do not (yet) exist for Africa, we present three systematic reviews of studies applying relevant elements, namely biophysical models, bio-economic models at farm household level, and agro-economic models at higher (regional or national) scale. The capabilities and limitations of these models and underlying data are summarised in view of the degree they meet pre-defined criteria for and comply with the demands (typical ex ante analyses/what-if questions) of evaluating relevant technological innovations in terms of their potential to maintain or increase crop yields and income at acceptable risk levels.

The chapter starts with a discussion of the regional scope and need for TIs based on recent Africa-wide modelling studies in Section 3.1. The following sections present the core of the Chapter. In section 3.2, we present results from a systematic review of biophysical modelling studies at various scales. Results of a systematic review on bio-economic modelling at farm household level are presented in section 3.3, and section 3.4 reports on relevant agro-economic modelling studies at higher aggregation levels than the farm. The chapter concludes with a section describing to what extent certain geographical areas, farming systems and ag-TIs have been represented by the various studies found.

3.1 Scope and need for technological innovation

One pathway to meeting the increase in future food demand of 70% or more by the year 2050 (Alexandratos and Bruinsma, 2012; Tilman et al., 2011) is to achieve more agricultural production on the existing agricultural land. This can be accomplished by reducing the gaps between farmers' actual crop yields and such yields that would be possible if optimal management were adopted, the so-called 'yield gap' (Yg, Van Ittersum et al., 2013). Assessment of the scope for narrowing these gaps relies on a robust reference database on yield gaps and their underlying causes (Van Bussel et al., 2015; Palosuo et al., 2015). Over the last two decades a number of different methods for yield gap analysis have been developed (see, e.g. Van Ittersum et al., 2013; Lobell et al., 2009) and applied to different crops from local (e.g. Kassie et al., 2014) to global scale (Neumann et al., 2010). Van Bussel et al. (2015) gives examples of up-scaling location-specific Yg estimates for a number of regions in Africa. Results of Yg information at national scale are reported in the Global Yield Gap Atlas (www.yieldgap.org) with results for some major cereals (maize, sorghum, millet, rice or wheat) also for various African countries (e.g. Burkina Faso, Ghana, Mali, Nigeria, Ethiopia, Kenya or Zambia).

The various methods of Yg analysis developed can be basically divided into two groups:

(i) one group follows the approach most comprehensively described by Van Ittersum et al. (2013), whereby yields simulated for the potential production situation (Yp) indicate the upper ceiling to serve as a reference yield for calculating the gap to actual yields (Ya) as obtained on farmer's fields. This specific yield gap (Yp-Ya) can in the best case be confirmed by potential growth trials in irrigated agriculture and on-farm field observations. The corresponding Y g for rainfed crop production is then calculated as the difference between yields simulated for water-limited production situation (Yw) and actual farmer's yields (Ya) (see, van Ittersum, 2013; Kassie et al., 2014);

(ii) another group follows an approach that does without simulated reference yields but relies purely on empirical data. Neuman et al. (2010) presents such approach for assessing global Y g for wheat, maize and rice, using a stochastic frontier production function (a Cobb-Douglas function) to calculate global datasets of maximum attainable grain yield and the gap between actual farmer's yields (Monfreda et al., 2008) and estimated frontier yields.

While the scope for innovation depends on the magnitude of Yg, the need for innovation also depends on current average production levels and their variability – co-determined by the exposure of agricultural systems to multiple (climate-induced) risks. Without even trying to be comprehensive, we would like to report on two different, huge research efforts that were recently performed in this respect by IFPRI (already mentioned in sub-section 2.3) and German research institutes together with African partners (Thomas & Rosegrant, 2015; Müller et al., 2014). These African-wide activities comprise an encompassing characterization of expected climate change effects on crop production potential and food security till 2050, including yield gap analyses for major crops (sub-section 3.1.2.1) and a multi-sector assessment of "risk hot spots" across Africa (sub-section 3.1.2.2) also indicating possible future shifts in the suitability of land for crop cultivation.

3.1.1 Comprehensive assessment by IFPRI

A wealth of information has been generated on expected changes in climate and yield changes for many crops, indicating the scope of productivity increase and innovation opportunities. The IFPRI-led work that was completed in 2013 comprises three major parts for East, West and Southern Africa (Hachigonta et al., 2013; Jalloh et al. 2013; Waithaka et al., 2013) – and each of these also includes a methodology chapter as well as separate chapters by country. Yield changes (%) for period 2000 to 2050 are presented for some major crops and generalized crop systems, showing mostly variable results (ranging from -25 to + 15%) depending on crop, region and climate scenario /climate model. Four climate models have been used in all analyses combined with the A1B SRES emission scenario. Climate simulation runs from the four GCMs were down-scaled to a resolution of 5 arc-minutes (Jones et al., 2009). For East Africa, for example, consistent negative yield changes are found for irrigated rice, rainfed sorghum and rainfed wheat. Even in such comprehensive studies, uncertainty may be underestimated considerably. That is partly due to the fact that only one crop modelling platform (DSSAT) (Jones et al., 2003) has been applied to assess the impacts on crop production, and also just one partial equilibrium agriculture model (IMPACT) for assessing economic effects and performing policy simulations (Rosegrant et al., 2008); moreover, the four different climate projections selected do not represent the entire spectrum of projected changes but data from climate simulation runs were rather selected based on availability/easy accessibility. No CO_2 fertilization effects on crops due to elevated atmospheric CO_2 up to year 2050 were taken into account. Though technological change has been somewhat considered, estimates were rather conservative and made in a simplified manner (Nelson et al., 2013). A Spatial Production Allocation Model (SPAM) (You et al., 2009), consisting of a set of raster datasets showing harvest area, production and yield for 20 crops or aggregates of crops was applied distinguishing three different management systems (irrigated, high-input rainfed, low-input rainfed). Inputs are allocated according to different levels of likelihood in indicating the specific locations of agricultural production. Crop production is allocated by SPAM from large reporting units (e.g. provinces or districts) to a raster grid at a spatial resolution of 5 arc-minutes inferring likely production locations from multiple indicators.

3.1.2 Hotspots of risk to food production

Another comprehensive Africa-wide study performed by PIK- CCAFS/CLIMAFRICA(BMBF) examined multi-sector risk hotspots (Müller et al., 2014). This study looks beyond agriculture and utilizes a large number of (40 SRES) climate scenarios with two assumptions on CO_2 effects in conjunction with six biosphere properties to map hotspots of climate change risks (on a grid and for different time slices) to food systems and hydrological systems for entire Sub-Saharan Africa. The six biosphere properties comprise: freshwater availability, flooding, dry periods, irrigation requirements, ecosystem productivity and crop yield. Though many climate scenarios (40) and biosphere indicators (6) are used in the analysis, results rely on only one impact model (LPJml) (Bondeau et al., 2007). Results are synthesized in different indicators. To calculate the indicator MSA (Multi-Scenario Agreement on changes to the worse), 480 scenarios (40 SRES x 2 CO_2 x 6 indicators) are considered (see, Fig. 4).

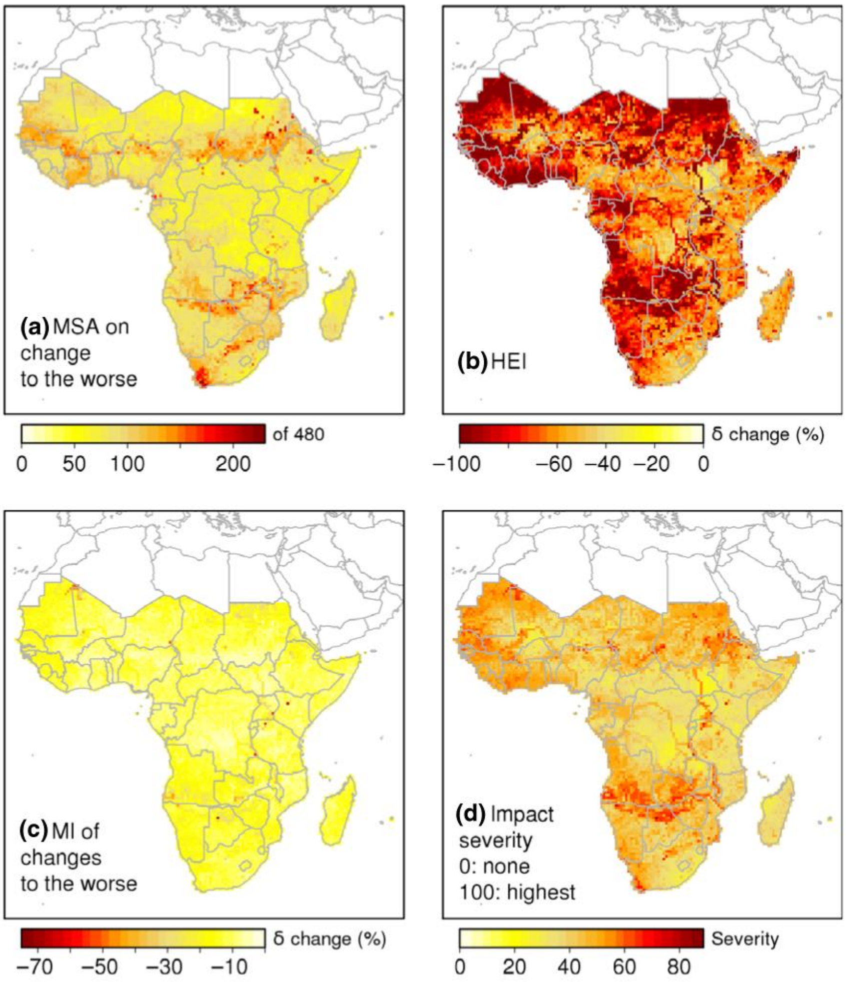


Figure 4: Hotspots of climate change in the 2080s

Note: Panel (a) displays the multiscenario agreement (MSA) of negative impacts to occur); panel (b) displays the high-end impact (HEI); panel (c) displays the median impact (MI) of all scenarios that lead to changes to the worse; and panel (d) displays the severity of climate change impacts. Impact severity of 0 indicates that there is no indication on changes to the worse in any scenario, a value of 100 would indicate that this pixel ranks highest in all three measures (MSA, HEI, MI) for each of the six biosphere properties (the six properties are: (i) freshwater availability, (ii) flooding, (iii) dry periods, (iv) irrigation requirements, (v) ecosystem productivity and (vi) crop yield).

Sources: Reprinted from Global Change Biology 20, Müller et al. (2014), Hotspots of climate change impacts in sub-Saharan Africa and implications for adaptation and development, page 13, Copyright (2014), with permission from John Wiley and Sons.

3.2 Biophysical models

We searched the SCOPUS database (http://www.scopus.com) for journal articles published between 1996 and 2015. In this review we considered modelling studies at different spatial scales with particular attention to national scale studies for the twelve PARI focal countries in Africa. But we also included studies for all other African countries as well as studies at supra-national/ (sub-) continental scale.

3.2.1 Review Methodology

Table 2 provides an overview of the applied search strategy. In a first step the SCOPUS database was searched for journal articles having the term 'crop model' or synonyms and terms related to the geographical coverage in the title, abstract or keywords. Within this group, the keywords were searched for terms related to management practices or innovations resulting eventually in 171 studies. A second search was performed seeking for studies related to climate change and adaptation (*Step 2*) which yielded 69 additional sources. These sources were then systematically reduced by including only those papers assessing the effects of innovative management practices and technologies on agricultural production by the use of biophysical models (*Step 3a*). The resulting list of 105 relevant studies was finally complemented by 35 additional papers identified through expert knowledge and cross-referencing (*Step 3b*) – eventually yielding 140 studies which were finally classified by geographical coverage, scale and primary innovation intention.

3.2.2 All African results

After completing the various steps of refining "search strings" and screening on relevance and supplementing databases from additional sources (as shown in section 3.2.1, above), we found 140 relevant biophysical modelling studies. Analysis revealed that the coverage of sub-regions and ag-TIs varied markedly. Most studies were found in East and West Africa, followed by Southern African countries; hardly anything was found for Northern and middle African countries. Regarding the share of different primary agro-technologies analyzed we found 45 on crop management, 35 on combined agro-technologies, 31 on soil nutrient management and conservation, 23 on water/soil moisture management, and 6 on other technologies such as mechanization or provision of a seasonal climate forecasting (see, Fig. 5).

Looking at the outcomes from the biophysical ex-ante evaluations, we found that many are (mostly) positive on effects of "single conventional" ag-TIs; the majority of studies is performed at "field scale" (see Figure 10) and focuses on the effects on productivity (sometimes yield stability); many of these studies were performed in climate variability and change /adaptation context. As shown in Fig. 6, the number of studies has grown considerably (approximately tripled) over the period 1996-2015.

Table 2: Search string for biophysical modelling search

Step 1		
Domain	**Search string for biophysical modelling search**	**Results**
Crop model	TITLE-ABS-KEY ("crop model*" OR "crop growth model*" OR "crop growth simulation" OR "crop simulation" OR "yield simulation" OR “biophysical model*”) OR TITLE-ABS-KEY ("agricult* model*" AND ("crop yield" OR "crop production" OR "agricult* production" OR "food security" OR "adaptive management" OR "cropping systems" OR "management practise" OR innovation OR technology	**171**
Management	KEY ("management practice" OR "cropping practice" OR "adaptive management" OR "agricultural management" OR innovation OR irrigation OR "water management" OR "growing season" OR "sowing date" OR "nutrient management" OR fertilizer OR adaptation OR adapting OR "soil fertility" OR technology OR conservation OR "planting date" OR "farming system")	
Coverage	TITLE-ABS-KEY (algeria OR angola OR benin OR botswana OR "Burkina Faso" OR burundi OR cameroon OR "Cape Verde" OR "Central African Republic" OR chad OR comoros OR congo OR djibouti OR egypt OR guinea OR eritrea OR ethiopia OR gabon OR gambia OR ghana OR "Guinea-Bissau" OR "Ivory Coast" OR kenya OR lesotho OR liberia OR libya OR madagascar OR malawi OR mali OR mauritania OR mauritius OR morocco OR mozambique OR namibia OR niger OR nigeria OR rwanda OR "São Tomé and Príncipe" OR senegal OR seychelles OR "Sierra Leone" OR somalia OR "South Africa" OR sudan OR swaziland OR tanzania OR togo OR tunisia OR uganda OR zambia OR zimbabwe OR africa OR ssa OR "Sub Saharan Africa"	
Step 2		
Domain	**Search string for biophysical modelling search**	**Results**
Climate Change & Adaptation	KEY ("climate change" AND ("crop production" OR "crop yield" OR "yield response" OR "food production") AND ("management practice" OR "farming system" OR "agricultural management" OR "adaptive management" OR "cropping pattern" OR “agricultural intensification” OR “cropping practice” OR “agricultural diversification” OR “alternative agriculture” OR sustainability OR “agricultural development”)	**69** additional studies
Coverage	TITLE-ABS-KEY (algeria OR angola OR benin OR botswana OR "Burkina Faso" OR burundi OR cameroon OR "Cape Verde" OR "Central African Republic" OR chad OR comoros OR congo OR djibouti OR egypt OR guinea OR eritrea OR ethiopia OR gabon OR gambia OR ghana OR "Guinea-Bissau" OR "Ivory Coast" OR kenya OR lesotho OR liberia OR libya OR madagascar OR malawi OR mali OR mauritania OR mauritius OR morocco OR mozambique OR namibia OR niger OR nigeria OR rwanda OR "São Tomé and Príncipe" OR senegal OR seychelles OR "Sierra Leone" OR somalia OR "South Africa" OR sudan OR swaziland OR tanzania OR togo OR tunisia OR uganda OR zambia OR zimbabwe OR africa OR ssa OR "Sub Saharan Africa"	
Step 3		
a)	Screening sources (TITLE-ABSTRACT-KEYWORDS) and assessment of relevancy	105 relevant studies
b)	Adding additional studies identified by cross-referencing	35
c)	Combining results	**140**

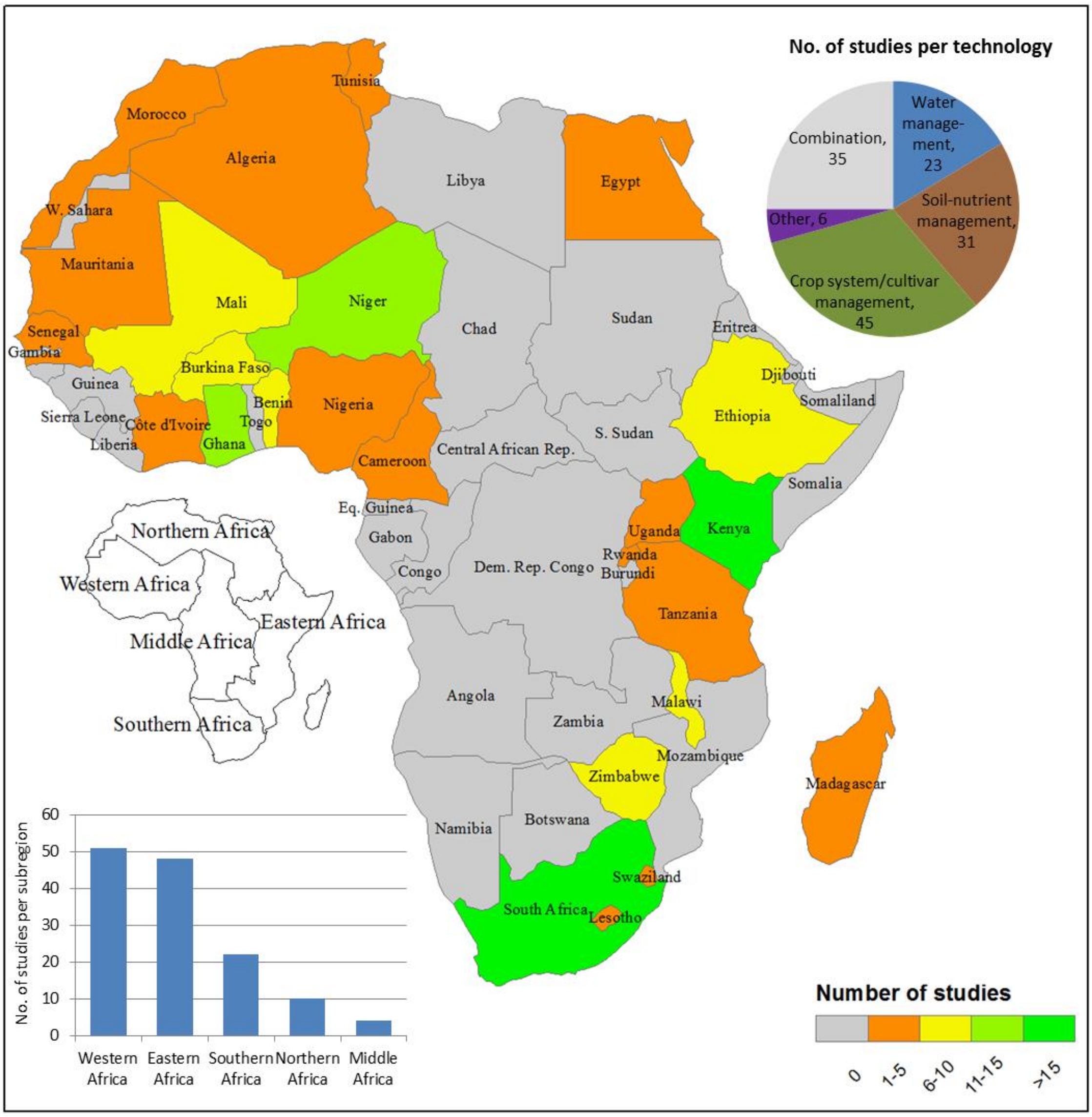


Figure 5: Review results: Number of biophysical modelling studies per country and subregion

3.2.3 Results for the twelve focal countries

Looking in more detail at the twelve focal countries (Fig. 7) we also find a rather unbalanced distribution, with most studies found in Kenya, Ethiopia, Mali, Malawi, and Ghana, whereas nothing or little was found in Togo, Zambia and Nigeria.

Very few of the biophysical studies include also information on various environmental impacts and profit, and there are few studies that present multi-scale or higher scale analyses; in the few cases where multiple scales are considered, there are more studies that scale up field-scale results to regional/sub-national – rather than to nation scale.

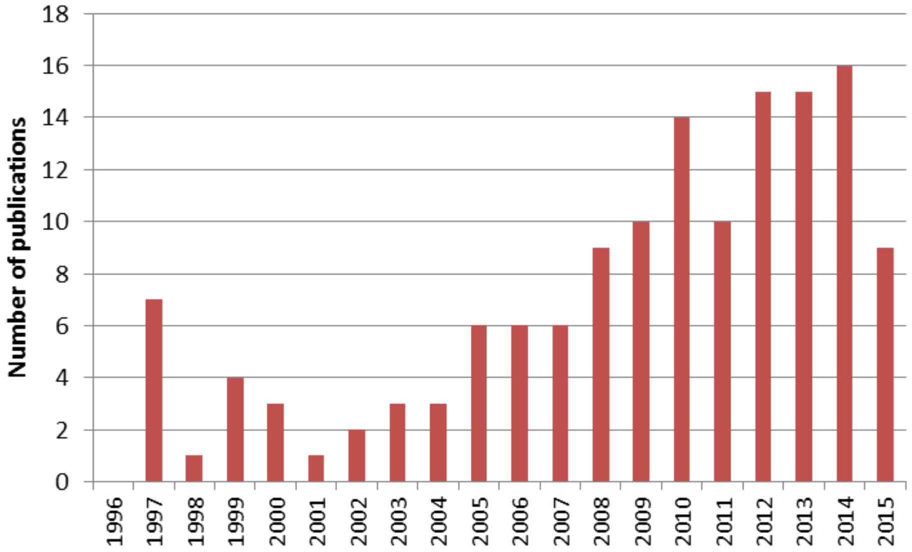


Figure 6: Number of biophysical modelling studies published per year from 1996 to 2015.

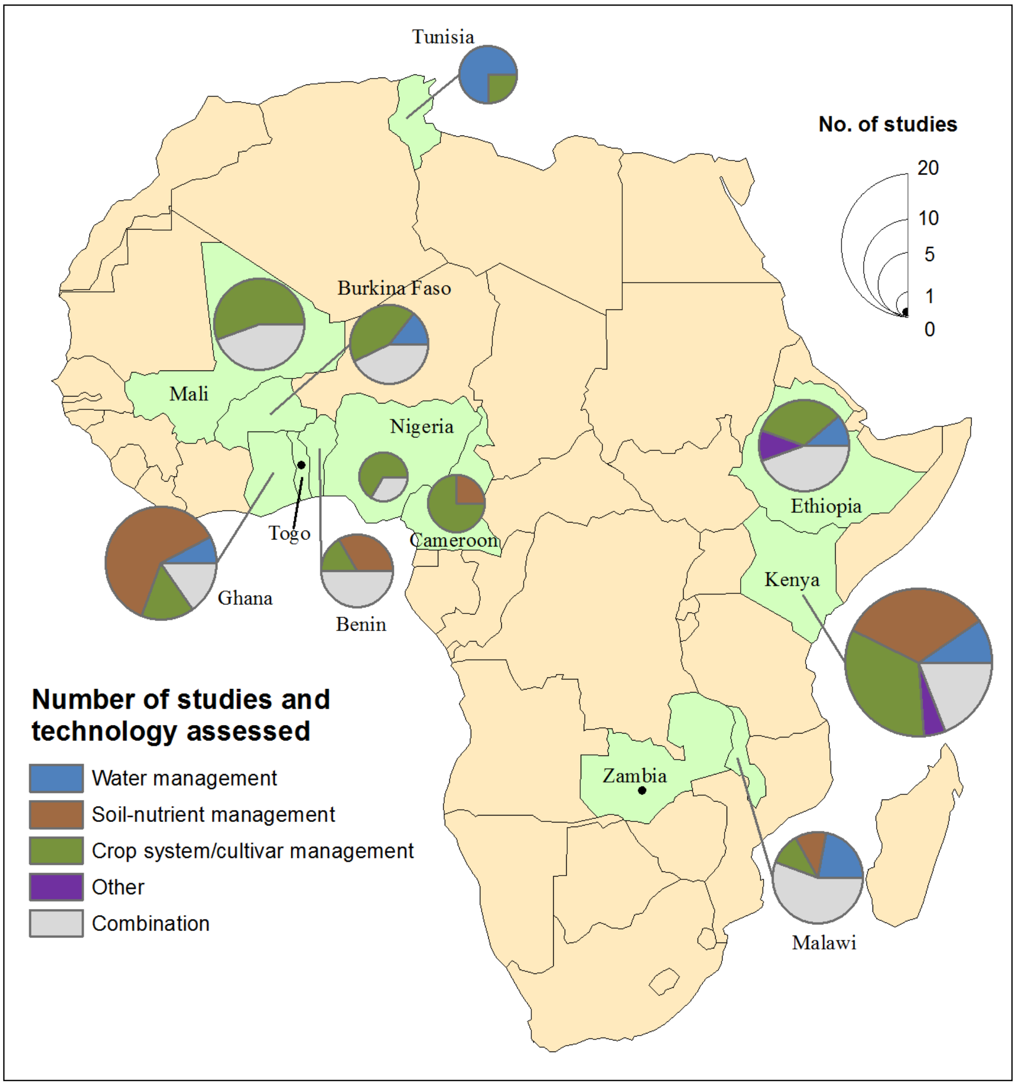
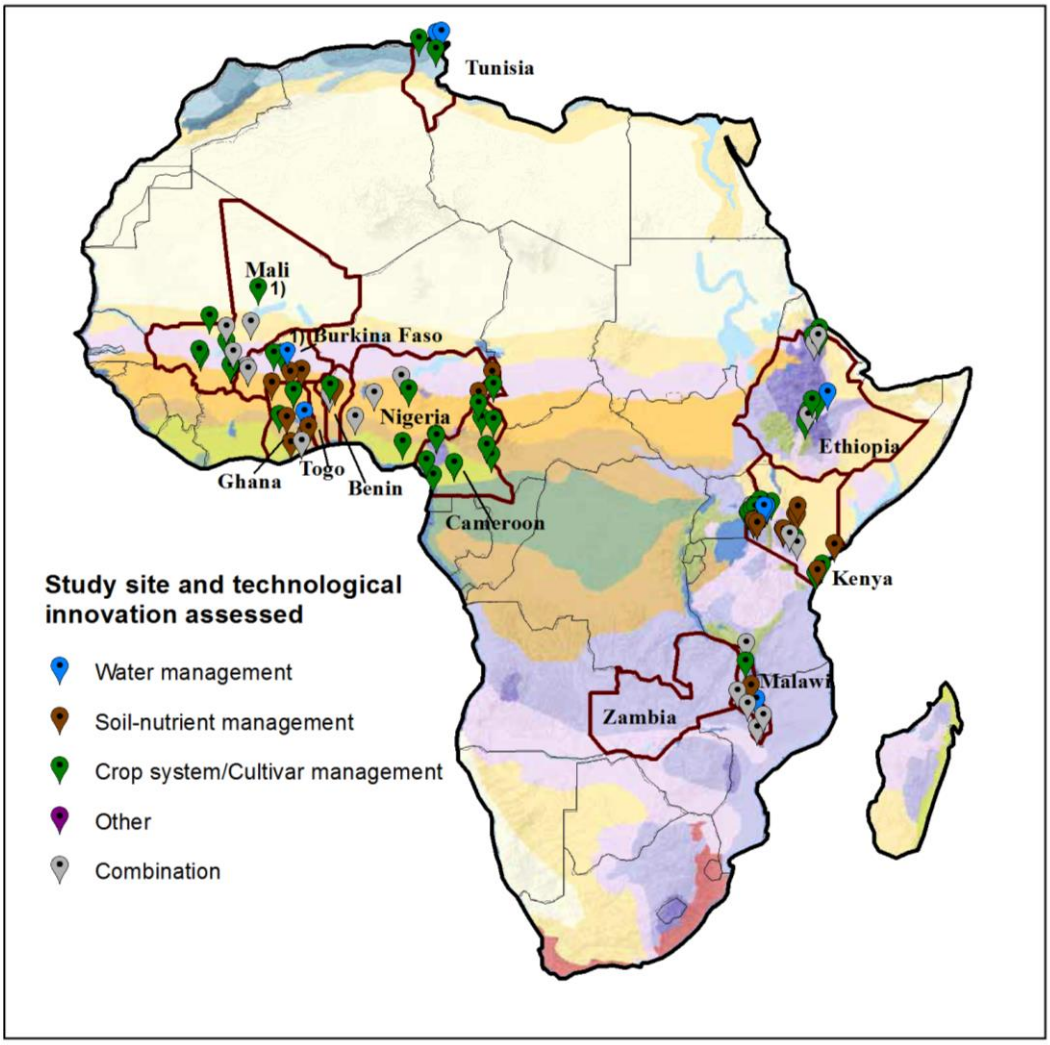


Figure 7: Review Results: Biophysical modelling studies in focal countries.

3.2.4 Remarks on coverage of area, farming systems and type of technology

- As mentioned already, the number of studies per country, agro-ecological zone or farming system (zone) and type of technology investigated varies a lot (see also Figures 7 to 9).
- The twelve focal countries are covered relatively well by the studies, which is partly due to e.g. CGIAR centre activities being concentrated in some countries (e.g. ICRAF and ILRI in Kenya and Ethiopia), large collaborative projects being very active in a few countries, such as WASCAL (in Ghana, Benin and Burkina Faso), previous long term projects by committed donors having focused on certain countries, e.g. Bill & Melinda Gates (e.g. in Malawi) or Wageningen UR International (e.g. in Mali); other examples include countries being especially vulnerable (such as Ethiopia) and therefore in the focus of multiple donors, or then having considerable own research funds (South Africa) and having the research infrastructure to perform the required studies.
- Typical farming systems of semi-arid and subhumid agro-ecological zones are better covered than other zones
- In most cases the innovation thoughts/orientation or motivation for the modelling study appears to be the search /evaluation of alternative crop or cropping systems that are designed to make more efficient use of (soil) water and nutrients, or, more generally, optimize resource efficiency (i.e. the use of soil, water and genetic resources)
- To a large degree the types of “technological innovation packages” analysed reflect the capability of the ex-ante evaluation tools – that is, the capability and limitations of existing crop-climate or ecophysiological simulation models such as DSSAT (Jones et al., 2003); APSIM (Keating et al. 2003), EPIC (Williams et al., 1983) or the SUCROS- and LINTUL-type Wageningen models (Van Ittersum et al., 2003), to name some of the most widely tested and applied.
- To some extent, we also can detect a clustering of studies by major crop modelling groups /or research groups heavily using the widely tested crop models mentioned above – that is studies carried out by Plant Production Systems or Agrosystems Modeling Groups (e.g. of CSIRO, IFPRI, INRA, University of Bonn, University of Florida or Wageningen University and Research Centre).
- In recent years, there have also been considerable spin-offs in Africa by global or regional (US or European-led) agricultural system modelling projects, such as AgMIP (Kihara et al., 2015), CCAFS (e.g. Thornton et al., 2011; Müller et al., 2014; Herrero et al., 2014), CropM component of MACSUR (often on a bi-lateral basis) (e.g. Kassie et al., 2015) or WASCAL (e.g. Webber et al., 2014) and Global Yield Gap Atlas (Van Bussel et al., 2015).

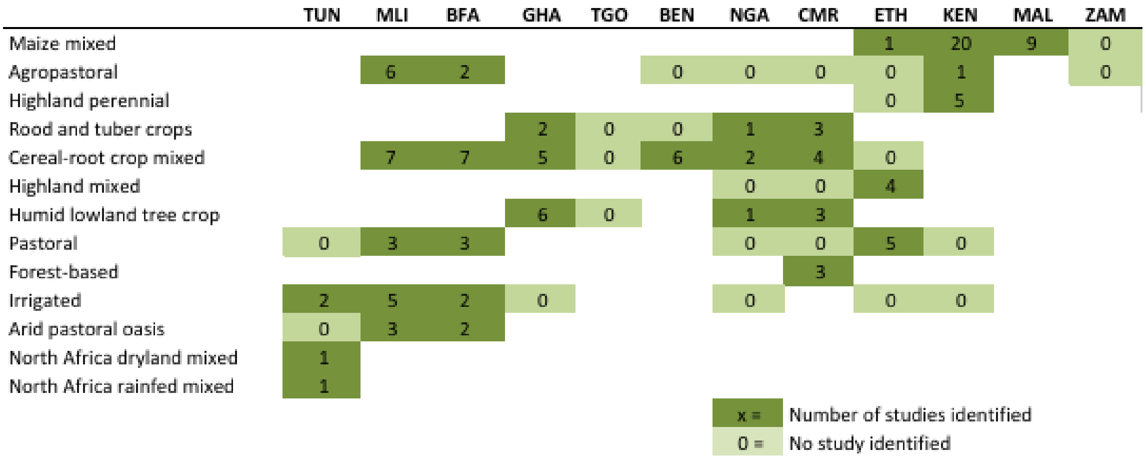


1) Study has been performed at country scale covering all relevant farming systems of the country.
Location indicates the centroid of the country.

Figure 8: Location of experimental site(s) (and/or weather stations) where biophysical study was conducted superimposed on farming systems map

Note: A single study can have multiple study locations

Source: based on Dixon et al. (2014); for legend see Fig.3.



	TUN	MLI	BFA	GHA	TGO	BEN	NGA	CMR	ETH	KEN	MAL	ZAM
Maize mixed									1	20	9	0
Agropastoral		6	2			0	0	0	0	1		0
Highland perennial									0	5		
Rood and tuber crops				2	0	0	1	3				
Cereal-root crop mixed		7	7	5	0	6	2	4	0			
Highland mixed							0	0	4			
Humid lowland tree crop				6	0		1	3				
Pastoral	0	3	3				0	0	5	0		
Forest-based								3				
Irrigated	2	5	2	0			0		0	0		
Arid pastoral oasis	0	3	2									
North Africa dryland mixed	1											
North Africa rainfed mixed	1											

x = Number of studies identified
0 = No study identified

Figure 9: Farming systems covered by biophysical modelling studies

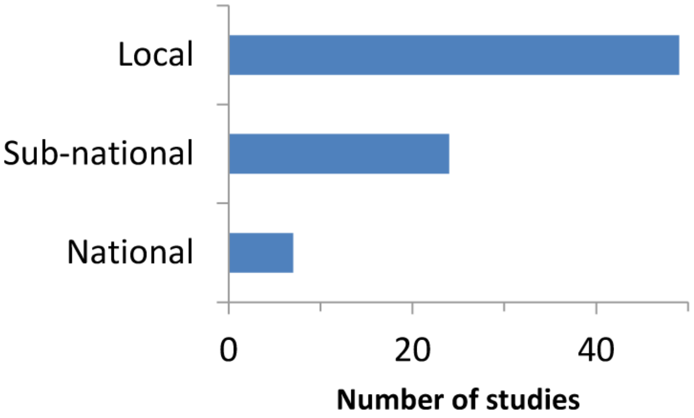


Figure 10: Number of biophysical studies performed in focal countries at different spatial scales

3.3 Agro-economic models at farm scale

This section focuses on the systematic review of agro-economic models used to assess technological innovations in Africa from 1996 to 2015. We choose to identify relevant peer reviewed publications because we seek to provide results that are both scientifically and empirically proven to allow the provision of science-based advice on the use of different types of agricultural technologies in Africa. The main objective of this section is to identify the types of agro-economic models applied in Africa to assess technological innovations during the last 20 years, their characteristics, the type of indicators assessed and their outcomes, and the gaps in terms of target areas in the focal countries and technologies assessed in PARI project. A closely related objective is to look at the methodological weaknesses of these agro-economic models with respect to (i) their integration with crop simulation models, other biophysical models and macro-economic models; (ii) their spatial features; (iii) and their capacity to integrate climate change, weather variability and decision behaviour of farmers under risk.

3.3.1 Review methodology

The review strategy employed consists of four steps. In the first step, we identified relevant search strings (see Table 3) that reflect the diverse terminology of agro-economic models. These search strings are not constrained by words related to innovation, as we assumed that all agro-economic models could potentially cover innovations. The search strings are introduced in Scopus search windows to identify peer reviewed articles, review articles, books, and book series published between 1996 and 2015 that apply any type of agro-economic models and that used the search terms in the title, abstract and key-words of their publications. We covered two scientific areas defined by Scopus: the social sciences and humanities, and the life sciences. Ten subject areas are covered: Agricultural and biological sciences; environmental science; social sciences; economics, econometrics and finance; veterinary science; computer science; decision sciences; mathematics; business, management and accounting; and multidisciplinary science. We searched for both English and French publications. This initial step yielded 1054 hits, which have been saved in the authors' Scopus database, and are available upon request.

Table 3: Search string for agro-economic modelling search with focus on farm scale

Search string for agro-economic modelling search with focus on farm scale
SCOPUS: TITLE-ABS-KEY ((("farm model*" OR "agriculture model*") AND "economic*") OR ("farm household" AND "model*") OR ("agricultural household AND “model*”) OR (("bio-economic*" OR “bio economic”) AND ("model*”) AND ("agriculture" OR "farm" OR "crop")) OR (("agent-based" OR “multi-agent” OR "agent based" OR “multi agent”)) AND ("model*") AND ("agriculture" OR "farm" OR "crop")) OR ("companion model*" AND ("agriculture" OR "farm" OR "crop")) OR ("agricultural system*" AND “model*” AND “economic*”) OR (("farm design" AND "model*" AND ("Agriculture" OR "farm" OR "crop")) OR (“agricultural production systems” AND “farm* level” AND “economic*”) OR (“model-based decision support” AND “farm*”) OR (“integrative model* approaches” AND “agric*”) OR (“whole-farm model*” AND “economic*”) OR (“farm-level model*” AND “economic*”) OR (“household level analyses” AND “economic”) OR (“agri-environmental system*” AND “economic*”) OR (“land based activit*” AND “economic”) OR (“multi agent system*” AND ("agriculture" OR "farm" OR "crop")) OR (“agricultural multi-market model*”) OR (“model based assess*” AND “economic*” AND ("agriculture" OR "farm" OR "crop")))

The second step of the review strategy consisted of an initial screening of the 1054 papers. This screening was done manually and directly in Scopus. It involved reading the title, keywords and abstract of the initial 1054 papers. This allowed the selection of studies that applied agro-economic models for assessing the impact of technological and policy innovations, literature reviews on the use of agro-economic models, and publications on scaling methodology with agro-economics models. All studies that at first glance applied (only) econometric analysis or budget analysis were eliminated at this stage. This initial screening allowed selection of 489 papers.

The third step of the review strategy consisted of screening the bibliographies of the nine review papers identified in the second step to identify relevant peer reviewed publications that we missed so far. The review papers are van Wijk (2014); van Wijk et al. (2014); Heckelei et al. (2012); Zander et al. (2008); Janssen and van Ittersum (2007); Acs et al. (2005); Brown (2000); Ruben et al. (1998) and Oriade and Dillon (1997). This step resulted in an additional number of 79 peer-reviewed publications that fit the criteria mentioned above.

The fourth step consisted of making a final screening of the publications identified in steps 2 and 3 to single out the ones that specifically applied agro-economic models to assess technological innovations in Africa. This has been done by re-reading the abstracts and if necessary by going through the contents of the paper. This process has led to the identification of a total of (only) 40 papers related to Africa, which we saved in an excel spreadsheet (see Table 4 for an excerpt). This database is described in the next subsection. The full list of papers reviewed is available at http://research4agrinnovation.org/publication/modelling_review.

Table 4: Excerpt from agro-economic modelling database

Bibliographic information	Region	Target region	Scale	Primary innovation intention	Evaluation of outcome indicators
Author Title Year Journal	Geographical coverage of study	Is focal country? Yes/No	1. Local 2. Sub-national 3. National 4. Supranational 5. Continental	1. Water management (e.g. irrigation type, rain water harvesting) 2. Soil-nutrient management (e.g. NPK, manure) 3. Crop/cultivar management 4. Other (mechanization, etc.) 5. Combination of 1-4	Win-win/Trade off/Mixed

3.3.2 Description of the database of relevant African studies

From Fig. 11 below it can be inferred that an average of two relevant papers have been published per year between 1996 and 2015, with a peak of six publications in 2014. This low publication rate is certainly related to the cost of implementing such studies and the interdisciplinary nature of the models. Many studies on technological innovations are ex-post impact assessment studies employing econometric analysis instead of the ex ante modelling techniques that are subject of this review.

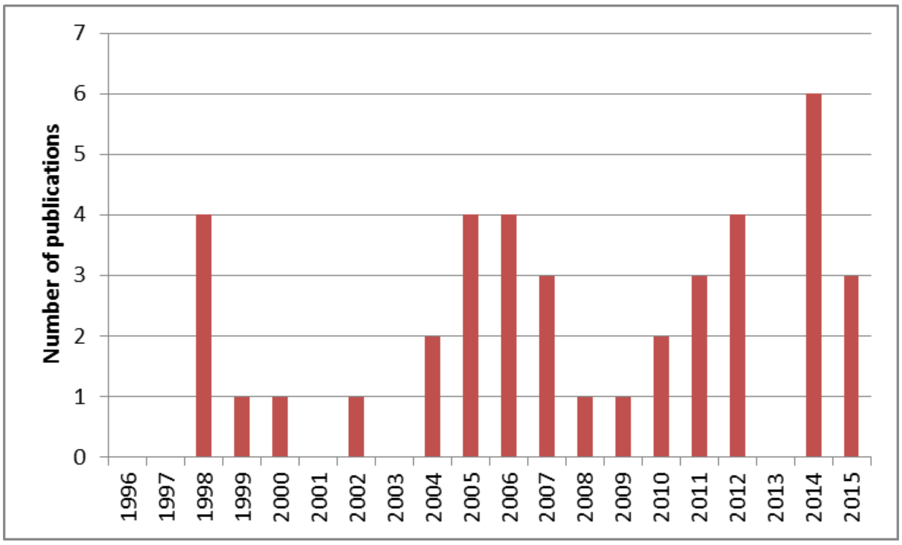


Figure 11: Number of agro-economic modelling studies published per year from 1996 to 2015

In total, 112 researchers have (co-) authored these 40 papers. These authors are affiliated to a total of 70 institutions around the world. Wageningen University and Research Centre in The Netherlands, Hohenheim University in Germany, the International Livestock Research Institute (ILRI) in Kenya host the highest number of authors. While most researchers have contributed to only one paper, there are notable exceptions. Mario Herrero from the CSIRO in Australia has co-authored four papers, followed by Thomas Berger from Hohenheim University in Germany, Kamel Louhichi from INRA in France, and Philip K. Thornton from ILRI/CCAFS in Kenya with each three papers. 19 authors contributed to two papers each and the remainder 86 to only one paper.

Most of the studies focus on Eastern Africa (54%), followed by Western Africa (28%), Northern Africa (10%) and Southern Africa (8%). No relevant studies have been identified for Middle Africa. Fig. 12 below shows the distribution of the number of studies per country in Africa. Note that two thirds of the studies (66 %) identified target one or more PARI focal countries (Burkina-Faso, Ethiopia, Ghana, Kenya, Malawi, Mali, Nigeria, and Tunisia).

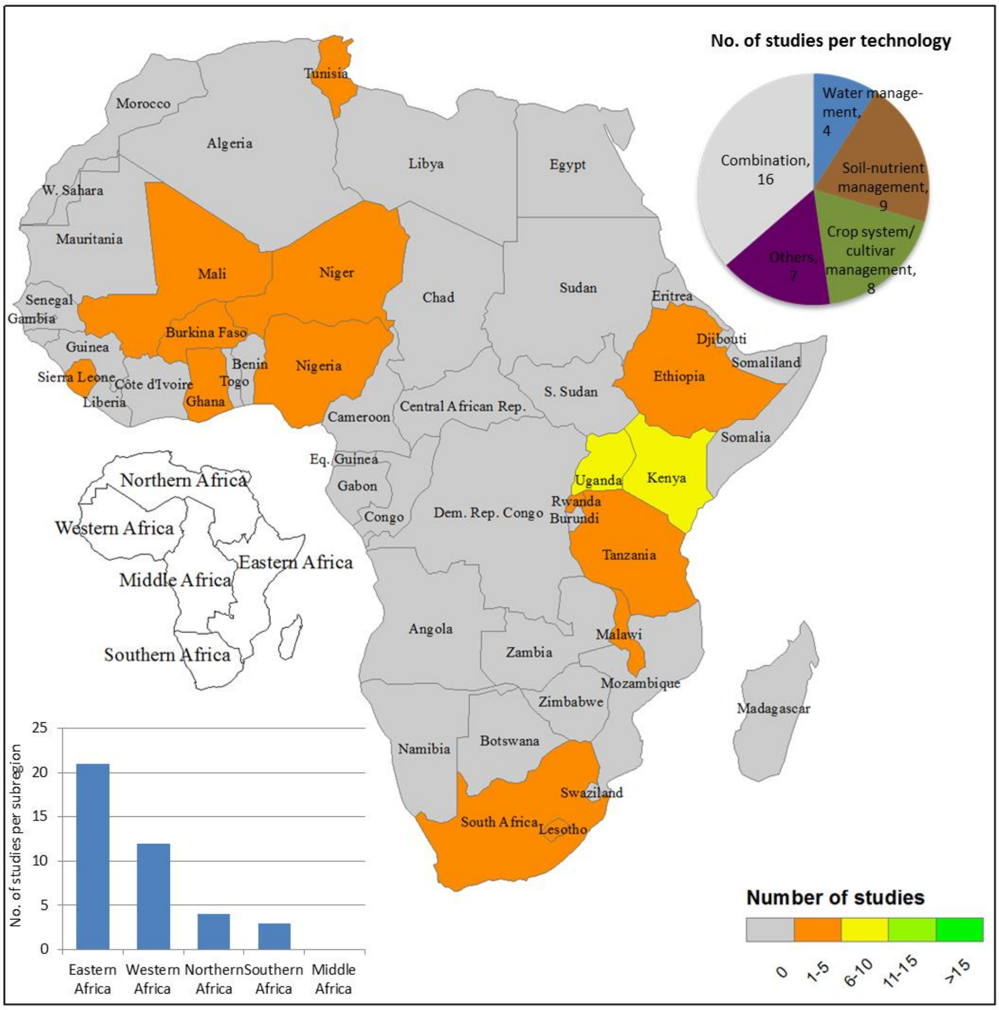


Figure 12: Number of agro-economic modelling studies per country and subregion

Kenya and Uganda have been in the focus of most agro-economic modelling studies with six studies each, followed by Tunisia and Ethiopia with four studies each, and Ghana and Mali with three studies each. Many African countries are not covered by this type of study including four focal countries of PARI: Benin, Togo, Cameroon and Zambia.3.3.3 Technological innovations assessed and in the focal countries

The technological innovations assessed in the 40 studies can be regrouped in four types: water management, soil nutrient management, crop and cultivar management, and other technologies including mechanization and provision of a seasonal climate forecasts (see Fig. 13 below). Note that the repartition of studies per group of technologies is not mutually exclusive because many studies (14) have studied a combination of two or three technologies.

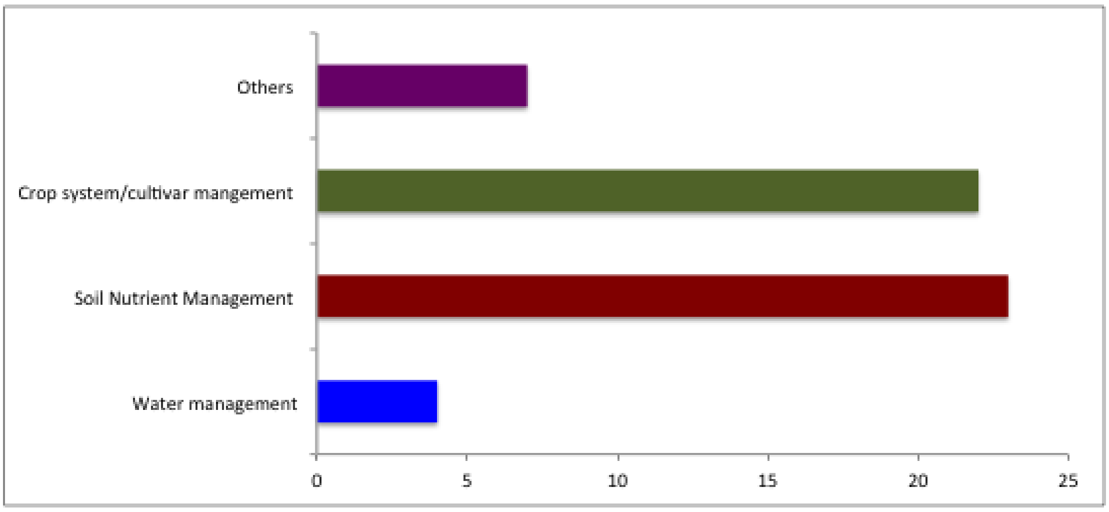


Figure 13: Number of studies per group of technologies and combination of technologies

The most frequently assessed technologies are those related to soil nutrient management and conservation (23 out of 40 studies). A substantial number of these studies (14) have assessed soil nutrient management and conservation in combination with crop/cultivar management, animal traction and/or water management (see, Fig. 14). Technologies related to soil nutrient management include the use of both organic and inorganic fertilizers. These studies have been implemented in two Western African countries, Mali (Dalton and Masters, 1998; Kruseman and Bade, 1998; Kuyvenhoven et al. ,1998) and Niger (La Rovere et al., 2005; Saqalli et al., 2011), and in five Eastern African countries, Rwanda (Bidogeza et al., 2015), Kenya (Tittonell et al., 2009; Valdivia et al., 2012), Ethiopia (Holden and Shiferaw, 2004; Kuiper and Ruben, 2007), Uganda (Berger et al., 2006; Woelcke, 2006, Schreinemachers et al., 2007), and Malawi (Dorward, 1999). The introduction of grain legumes in the cropping system to improve soil nutrient management has been covered by four studies in Malawi (Franke et al. 2014), Tunisia (Louhichi et al., 2010), Ghana (Yiridoe et al., 2006) and Mali (Kuyvenhoven et al., 1998). Soil conservation practices involved the assessment of technologies such as contouring, buffer strips, terracing, trenches, reduction of tillage, avoidance of bare fallow, alley cropping, cut-and-carry mulching system, agro-forestry and introduction of perennial crops. These studies have covered three sub-regions in Africa. Nigeria in Western Africa (Tré and Lowenberg-Deboer, 2005), Rwanda (Bidogeza et al. 2015), Kenya (Stephens et al., 2012), Uganda (Woelcke, 2006) and Ethiopia (Shiferaw and Holden, 2000; Holden and Shiferaw, 2004, Okumu et al., 2004) in Eastern Africa and Tunisia in Northern Africa (Alary et al., 2007; Louhichi et al., 2010).

22 studies have applied agro-economic models to assess the impact of crop and cultivar management in Africa. This involves the study of crop choice decision and cropping strategies, the assessment of diversification strategies with cash crop, forage and grain legume production, the use of improved varieties, and management strategies such as crop-livestock integration, planting time and number of weedings. Crop choice decision and cropping

strategies have been studied by González-Estrada et al. (2008) in Ghana and Holden and Shiferaw (2004) in Ethiopia. Diversification strategies have been studied by Herrero et al. (2014) and Tittonell et al. (2009) in Kenya, Franke et al. (2014) in Malawi, Louhichi et al. (2010) in Tunisia, Komarek (2010) in Uganda, Yiridoe et al. (2006) in Ghana and Okumu et al. (2004) in Ethiopia. The use of improved crop varieties has been studied by Louhichi and Gomez y Paloma (2014) in Sierra Leone on NERICA, Ilukor et al. (2014) on drought resistant and virus free sweet potato planting material, Schreinemachers et al. (2007) on improved maize seeds in Uganda and Wossen et al. (2014) on early maturing crop varieties in Ghana. The assessment of farm management strategies has been studied by Waithaka et al. (2006) on change in farm enterprise mixes in Kenya, Dorward (1999) on planting time and number of weeding in Malawi, Dalton and Masters (1998) on crop-livestock management practices in Mali, and Komarek and Ahmadi-Esfahani (2011) on recommended farm management practices in Uganda.

Four studies covered water management technologies, which include the expansion of irrigation access or increasing the supply of irrigation water in Ghana and Burkina Faso (Sanfo and Gérard, 2012; Wossen et al., 2014) and assessing the sustainability of irrigation systems or reducing the supply of irrigation water in Tunisia (Jeder et al., 2011; Belhouchette et al., 2012).

Seven studies have assessed other technologies or farm management. These technologies include mechanization by animal traction in Tanzania (Tiberti and Tiberti, 2015) and Burkina-Faso (Sanfo and Gérard, 2012), and by tractor in Nigeria; the provision of seasonal climate forecasts to farmers by Bharwani et al. (2005) in South Africa and Ziervogel et al., (2005) in Lesotho; and the assessment of transport infrastructure and non-selective grazing system in Kenya and South Africa, respectively (Omamo, 1998, Beukes et al., 2002).

Fig. 14 shows the distribution of technologies assessed in each of the focal countries. Soil nutrient management is the most assessed technology of the 27 studies addressing the project focal countries. This technology has been studied with agro-economic models in all focal countries but Burkina-Faso, Togo, Benin and Cameroon and Zambia. Crop system/crop cultivar management has been assessed only in three out of the twelve focal countries – Burkina-Faso, Nigeria, Ethiopia and Kenya. Water management technologies have been assessed only in Tunisia, Burkina-Faso and Ghana.

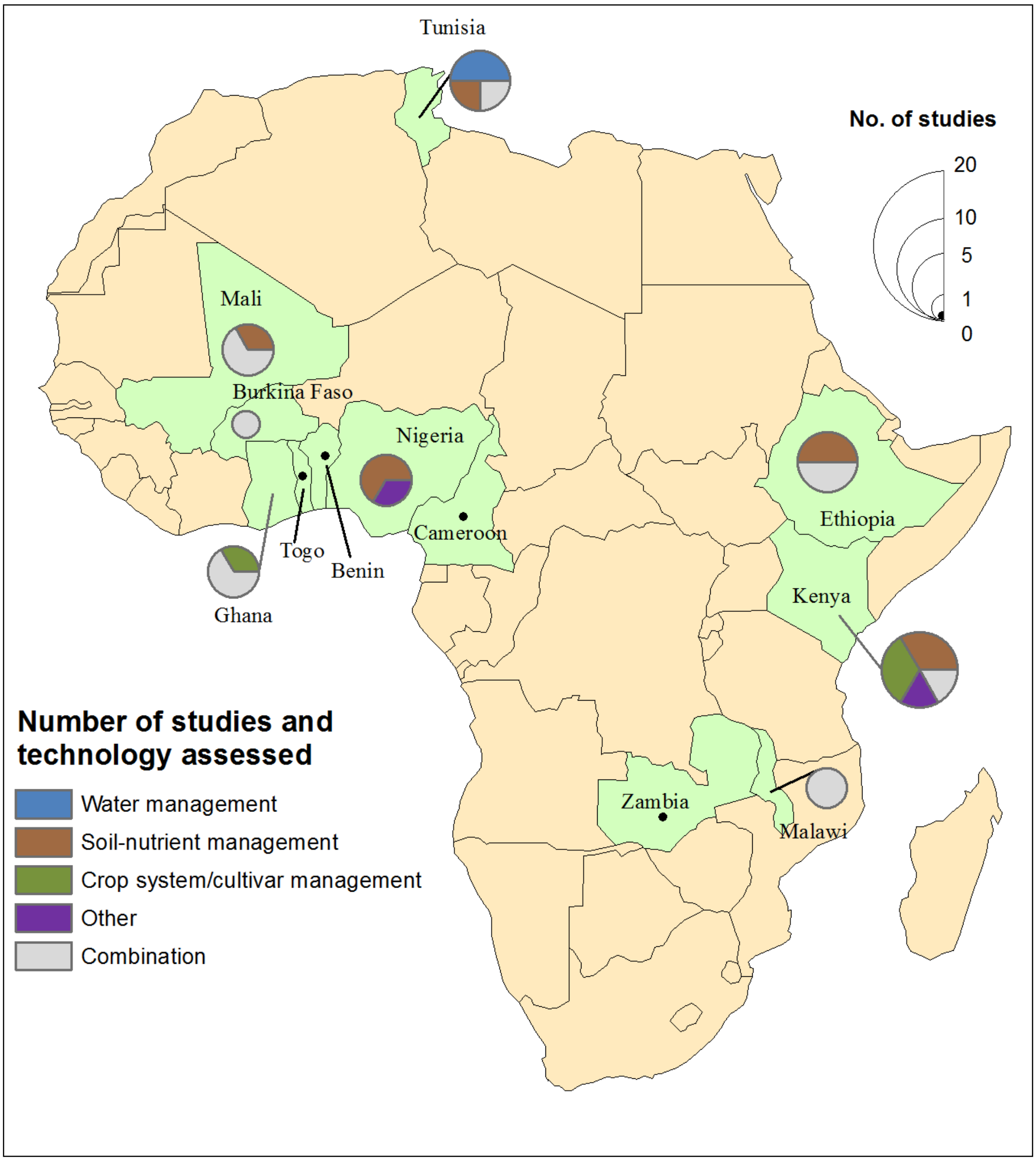


Figure 14: Number of agro-economic modelling studies and type of technologies assessed in focal countries

3.3.4 Types and characteristics of agro-economic models used to assess technological innovations in Africa

The agro-economic models applied to assess technological innovations in Africa can be regrouped in three broad types of models: multi-agent system models (Bharwani et al. 2005, Ziervogel et al. 2005, Saqalli et al. 2011), combination of multi-agent system and mathematical-programming models (Berger et al. 2006, Schreinemachers et al. 2007, Komarek and Ahmadi-Esfahani 2011, Wossen et al. 2014) and mathematical-programming models (all other studies). As can be seen from Fig. 15 below, mathematical programming of representative farm households is the dominant modelling strategy used to assess technological innovations by agro-economic models in Africa. It is followed by the combination of mathematical programming and multi-agent system (MAS) modelling, which is used in four studies of our sample. These studies involve aggregation of representative farm household models accounting for social, economic and/or spatial interactions. Pure MAS studies are based on informal behavioural rules often generated through role playing. For all model types, the standard method for model validation – if validation is discussed - is comparison of the baseline results to the information from the survey used for model estimation.

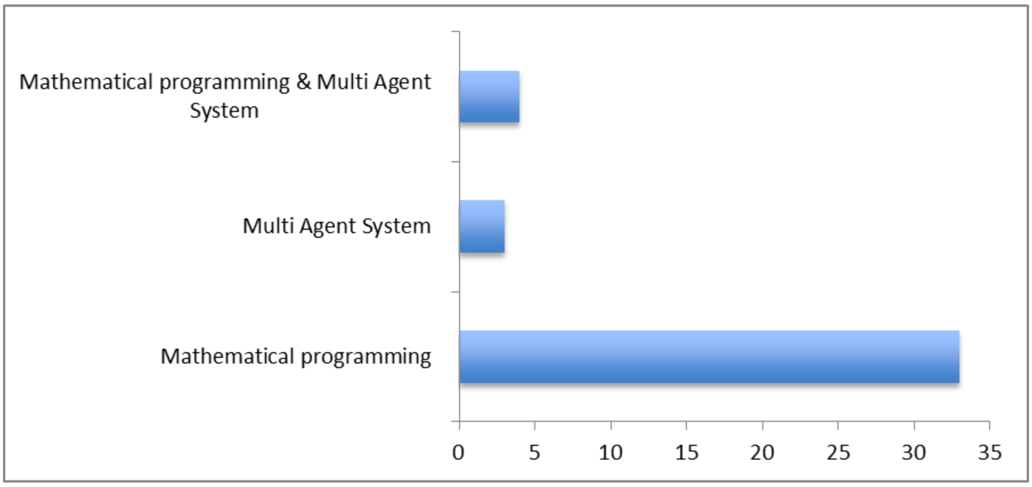


Figure 15: Type of agro-economic models

Most mathematical programming studies claim only local representativeness; three studies state that their farm models are representative at subnational level, two at national level (one of these only for a specific farm type). Multi-agent system studies focus on specific villages, while combined studies aggregate to (sub-) district scale.

Almost two thirds of the studies (62%) have explicitly taken the “time dimension” into account and thus use dynamic models. Such models are important in assessing technological innovations because they allow interaction and feedback mechanisms between the economic and the bio-physical components of the model (Brown, 2000; Janssen and van Ittersum, 2007).

Regarding the coverage of African farming systems, most of the studies have covered (in order of importance) the maize mixed, agro pastoral, highland perennial and highland mixed farming systems (see Fig. 16). The cereal root crop mixed, irrigated, pastoral, humid lowland tree crop and North Africa dryland mixed farming systems are less covered.

The time horizon covered by the agro-economic models is around 16 years on average. 43% of the studies focus on a short-term time horizon (lower or equal to five years) and the others on long-term time horizon (higher than five years).

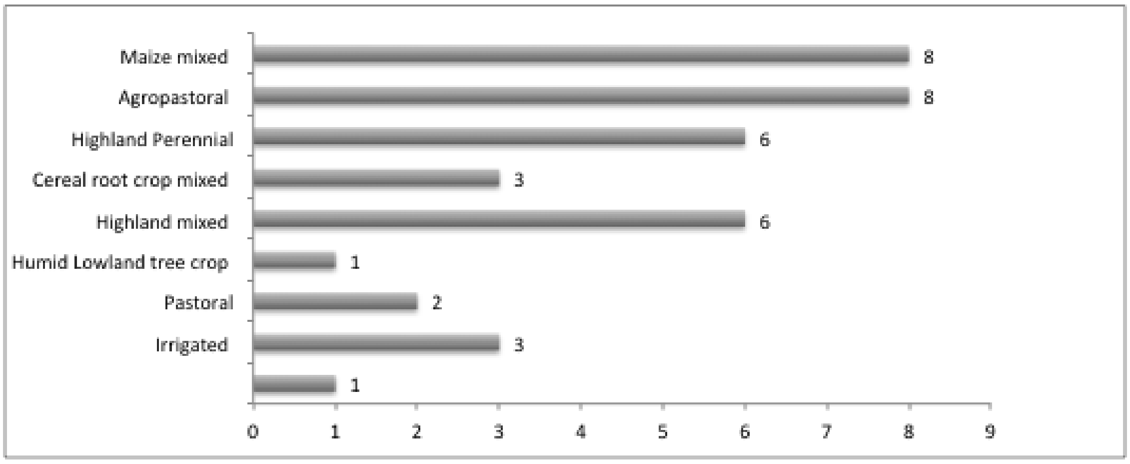


Figure 16: Number of agro-economic studies per major farming systems in Africa

Sixteen (i.e. 40%) out of 40 studies take risk into account. Out of these, six have integrated risk in terms of production and price variability coupled with the risk preferences of farmers. Production variability involves the effect of variable rainfall patterns but implicitly also integrates other sources of risk such as pests and diseases. Eight studies have explicitly taken rainfall risk into account by modelling the effect of variable rainfall patterns on crop production, but have not explicitly integrated risk adverse behaviour of the farmer. One study has modelled rainfall variability with a discrete set of states of the nature of rainfall conditions and integrates these in the mathematical programming model through the effect of rainfall conditions on technical coefficients in production activities. Another study used a safety first approach based on a lexicographic ordering of objectives to integrate yield risk associated with dry spells and timing of the start of the rain.

3.3.5 Impact of technological innovations assessed by agro-economic models

Fig. 17 presents the impact indicators of technological innovations assessed by the agro-economic models for Africa. Three types of indicators can be distinguished: income, food security, and environmental sustainability. Food security indicators reflect food availability and access but not nutritional status. Despite the current surge of research on the linkages between agriculture and nutrition, there is insufficient knowledge about how changes in agricultural production affect nutrition through changes in food availability, income and women (dis-) empowerment to include nutrition as an indicator in bio-economic models.

It is critical for the studies to focus on the three indicators all together if their purpose is to test the impact of technological innovations on farmers' welfare while preserving the natural resources base. Focusing only on income and environment and ignoring food security means implicitly assuming that there is no market failure for access to food, which is rarely the case in developing countries. In spite of this, only four studies have considered all three indicators.

Most studies (14 out 40) have focused on assessing the impact of technological innovations on farm household income as well as environmental indicators such as soil nutrient balance and soil erosion or salinization. Next, income alone and the combination of food security and income are the most studied indicators. Few studies have focused on only food security, only environment, or food security and environment.

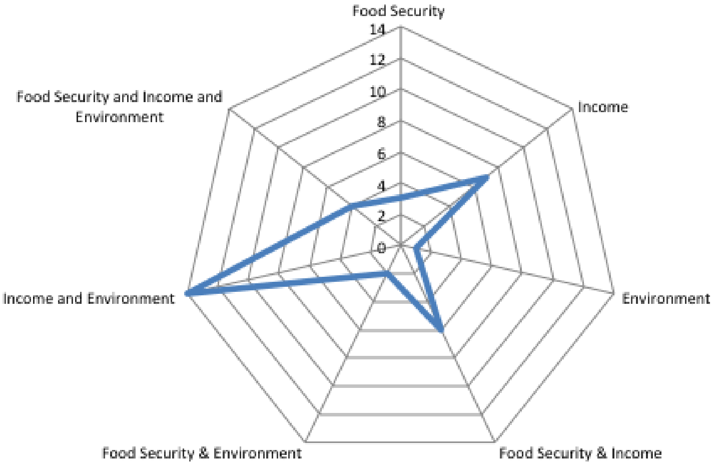


Figure 17: Impact assessment of sustainability indicators (N =39)

Most of the technological innovations assessed yield win-win outcomes for food security and income. The results are balanced for food-security and environment, income and environment, and food security, income and environment (see Table 5). This is indicative of the complexity to achieve both welfare and environment goals. We failed to classify the study of Herrero et al. (2014) because its main focus is on modelling the future spatial distribution of farming systems.

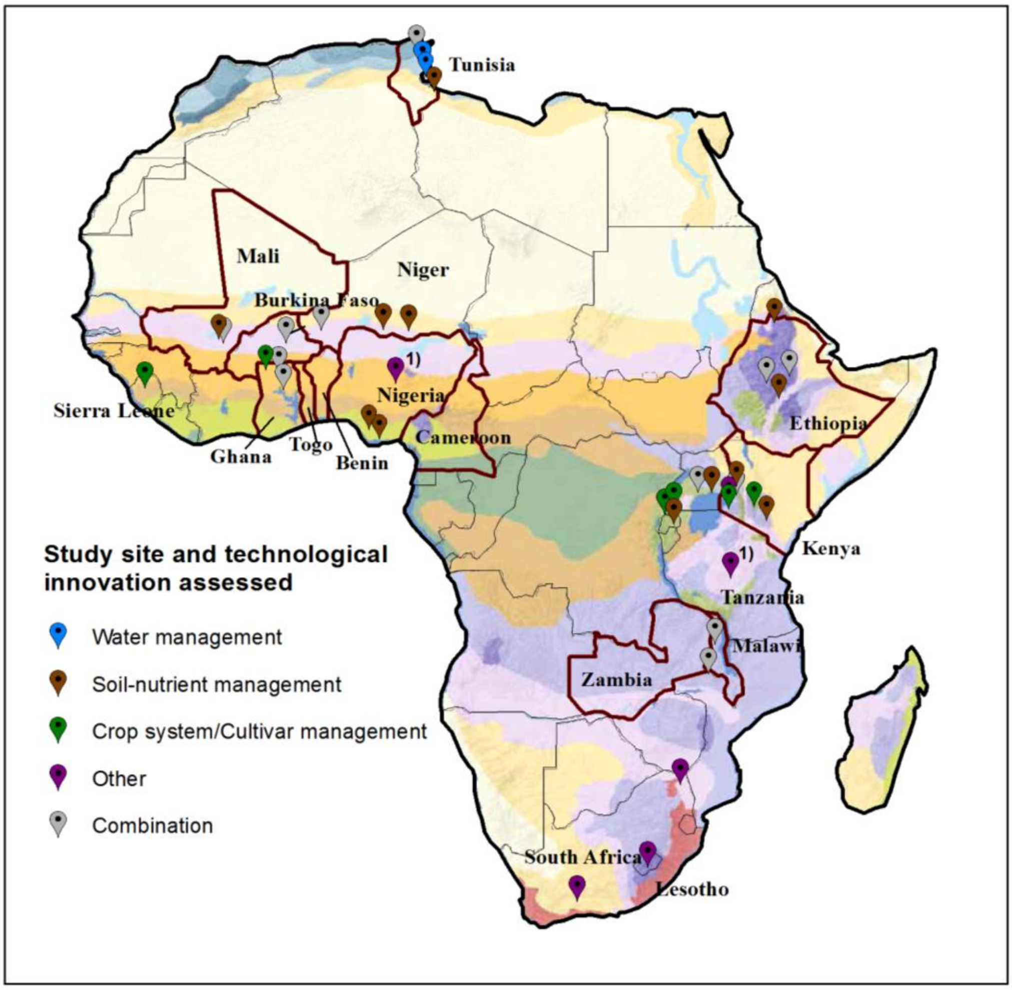
Table 5: Outcomes of sustainability indicators (N=37).

	Win	Mixed	Win-Win	Trade-off
Food security	1	2		
Income	4	3		
Environment		1		
Food security & Income			5	1
Food security & environment			1	1
Income & Environment			7	7
Food security, income & environment			2	2
Total	**5**	**6**	**15**	**11**

Note: The 37 studies are classified on whether their results show gains (Win) or variable outcomes (Mixed) for single indicators, or for multiple indicators gains only (Win-Win) or gains in one or more indicators (Trade-off).

3.3.6 Agro-economic models and farming systems in focal countries: the gap

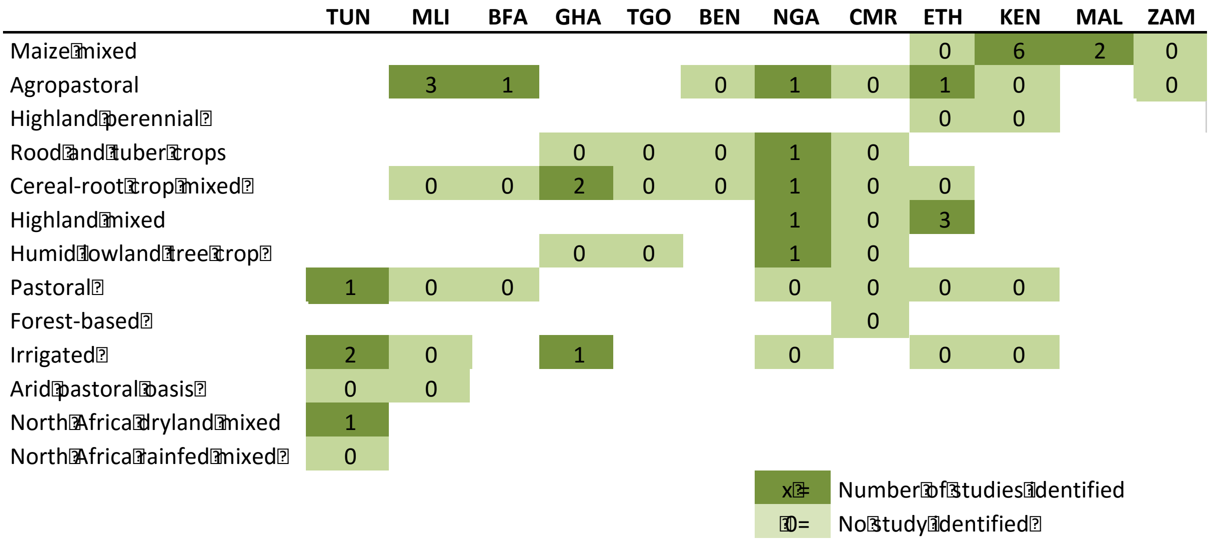
In this subsection we overlay the exact locations of the studies reviewed with the generalized farming systems map to indicate their representativeness. Figs. 18 and 19 below show the different existing farming systems in each focal country and whether our systematic search has identified any agro-economic model assessing any technological innovation in the given farming system areas during the last 20 years. There are still many farming systems in the project focal countries that have not been studied. Farming systems in Togo, Benin, Cameroon and Zambia are not covered at all by the studies identified. In Eastern Africa, the highland perennial, root and tuber crop, pastoral and irrigated farming systems have not been assessed. In western Africa, the root and tuber crop, humid lowland tree crop, pastoral and arid pastoral oasis farming systems are not studied so far. In northern Africa –Tunisia, there were no studies covering the arid pastoral and North Africa rainfed mixed farming systems.



1) Study has been performed at country scale covering all relevant farming systems of the country. Location indicates the centroid of the country.

Figure 18: Location of experimental site(s) (and/or weather stations) where agro-economic modelling study was conducted superimposed on farming systems map

Source: based on Dixon et al. (2014), for legend see Fig.3.



	TUN	MLI	BFA	GHA	TGO	BEN	NGA	CMR	ETH	KEN	MAL	ZAM
Maize mixed									0	6	2	0
Agropastoral		3	1			0	1	0	1	0		0
Highland perennial									0	0		
Rood and tuber crops				0	0	0	1	0				
Cereal-root crop mixed		0	0	2	0	0	1	0	0			
Highland mixed							1	0	3			
Humid lowland tree crop				0	0		1	0				
Pastoral	1	0	0				0	0	0	0		
Forest-based								0				
Irrigated	2	0		1			0		0	0		
Arid pastoral oasis	0	0										
North Africa dryland mixed	1											
North Africa rainfed mixed	0											

x = Number of studies identified

0 = No study identified

Figure 19: Farming systems covered by integrated modelling studies

3.3.7 Conclusions

Most of the models are based on mathematical programming of representative farms. Few studies use multi-agent system models. A slightly larger number of studies claims to use a combination of mathematical programming and multi-agent modelling. Their interpretation of multi-agent modelling differs from the highly inductive, largely qualitative decision rule-based approach of pure multi-agent studies. The combined studies aggregate the results from representative farm models in an iterative approach using formal, often theory-based rules for social, economic and spatial interactions. They are therefore an extension of the standard farm-level mathematical programming models that ignore aggregation issues such as price effects of increases in product supply (Berger et al., 2006).

We failed to identify models that have implemented a direct linkage with macro-economic models or sector models. This is critical for the scaling-up of model results from farm level to regional (i.e. sub-national) or national level to determine boundary conditions (see Section 5). As indicated, several studies aggregate farm-level models to small regions, but higher aggregation levels are not accounted for. We did find studies that combined agro-economic models with crop simulation models and ecological models to explicitly integrate the dynamics of crop growth and soil nutrient stocks.

Few studies focused on water management and mechanization, contrary to the more popular assessment of soil nutrient management and crop system and cultivar management. In the context of increasing climate variability and climate change, this is striking as in many regions water management is becoming increasingly critical. In this respect it is also important to note that only 40 percent of all models take risk into account.

No studies have been identified in Togo, Benin, Cameroon and Zambia on the impact of technological innovations by agro-economics models. Furthermore, many countries' farming systems have not been studied so far: i.e. the root and tuber crop, cereal-root crop mixed, humid lowland tree crop, highland mixed in Western and middle Africa; arid pastoral-oasis in Northern and Western Africa; Pastoral, irrigated in western and eastern Africa.

Most studies have focused on food security and environment and less on other combinations of food security with environment and income dimensions. Nutrition security, which is high on the current policy agenda, is not accounted for. Finally, it was noticed that technological innovations do not systematically result in win-win-win outcomes regarding income, food security and environment indicators.

3.4 Integrated agro-economic models at higher aggregation levels than farm

A systematic literature search was performed to identify modelling studies at higher aggregation level than a household or a farm. The search was conducted by using Scopus. Complementary publications were included by using Agrodep website[4]. The search string contained three components: 1) model type, 2) country information and 3) agricultural key words (see, Table 6). The Scopus search was limited to peer-reviewed publications which had appeared since 1995.

The search produced 365 publications. Abstracts of these publications were reviewed to determine which of them were relevant. After the review, 59 publications were included for further analysis. Selected articles were required to focus on ag-TI and to carry out ex-ante modelling. Integration of agro-ecosystems and -economic modelling was not required as a method of study, because there seemed to be too few publications focusing on integrated modelling. Many articles did not examine ag-TI explicitly, but they examined innovations at a more general level or examined impacts of different shocks in the context of different production systems.

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[4] http://www.ifpri.org/project/agrodep

Table 6: Search string for agro-economic modelling search with focus on higher aggregation level

Search string for agro-economic modelling search with focus on higher aggregation level
SCOPUS: TITLE-ABS-KEY (((model AND agriculture AND economic AND (national OR international OR sector* OR equilibrium OR economy)) OR (partial AND equilibrium) OR (general AND equilibrium)) AND (agriculture OR food OR (natural AND resources) OR (crop AND production) OR farming OR (climate AND change) OR (sustainable AND intensification) OR cropping OR (agric* AND innovation) OR (agric* AND policy) OR (agricultural AND development)) AND (algeria OR angola OR benin OR botswana OR "Burkina Faso" OR burundi OR cameroon OR "Cape Verde" OR "Central African Republic" OR chad OR comoros OR congo OR djibouti OR egypt OR guinea OR eritrea OR ethiopia OR gabon OR gambia OR ghana OR "Guinea-Bissau" OR "Ivory Coast" OR kenya OR lesotho OR liberia OR libya OR madagascar OR malawi OR mali OR mauritania OR mauritius OR morocco OR mozambique OR namibia OR niger OR nigeria OR rwanda OR "São Tomé and Príncipe" OR senegal OR seychelles OR "Sierra Leone" OR somalia OR "South Africa" OR sudan OR swaziland OR tanzania OR togo OR tunisia OR uganda OR zambia OR zimbabwe OR africa OR ssa OR "Sub Saharan Africa" OR sahel)) AND (LIMIT-TO (PUBYEAR , 2015) OR LIMIT-TO (PUBYEAR , 2014) OR LIMIT-TO (PUBYEAR , 2013) OR LIMIT-TO (PUBYEAR , 2012) OR LIMIT-TO (PUBYEAR , 2011) OR LIMIT-TO (PUBYEAR , 2010) OR LIMIT-TO (PUBYEAR , 2009) OR LIMIT-TO (PUBYEAR , 2008) OR LIMIT-TO (PUBYEAR , 2007) OR LIMIT-TO (PUBYEAR , 2006) OR LIMIT-TO (PUBYEAR , 2005) OR LIMIT-TO (PUBYEAR , 2004) OR LIMIT-TO (PUBYEAR , 2003) OR LIMIT-TO (PUBYEAR , 2002) OR LIMIT-TO (PUBYEAR , 2001) OR LIMIT-TO (PUBYEAR , 2000) OR LIMIT-TO (PUBYEAR , 1999) OR LIMIT-TO (PUBYEAR , 1998) OR LIMIT-TO (PUBYEAR , 1997) OR LIMIT-TO (PUBYEAR , 1996)) AND (LIMIT-TO (DOCTYPE , "ar") OR LIMIT-TO (DOCTYPE , "re"))

3.4.1 Results

The Republic of South Africa was the country that was mentioned most frequently (11 studies) in the reviewed studies. For many African countries no publications were identified. Next to the Republic of South Africa, Ethiopia, Ghana, Senegal and Morocco were among those countries mentioned most frequently, all with less than five publications per country (Fig. 20). There were also nine studies with a regional (multi-country), continental or global focus (a global analysis providing results for Africa). National-level analysis, including sector-specific analyses, was carried out in 37 studies. Regional, village-level or sub-sectoral analysis was carried out in 13 studies.

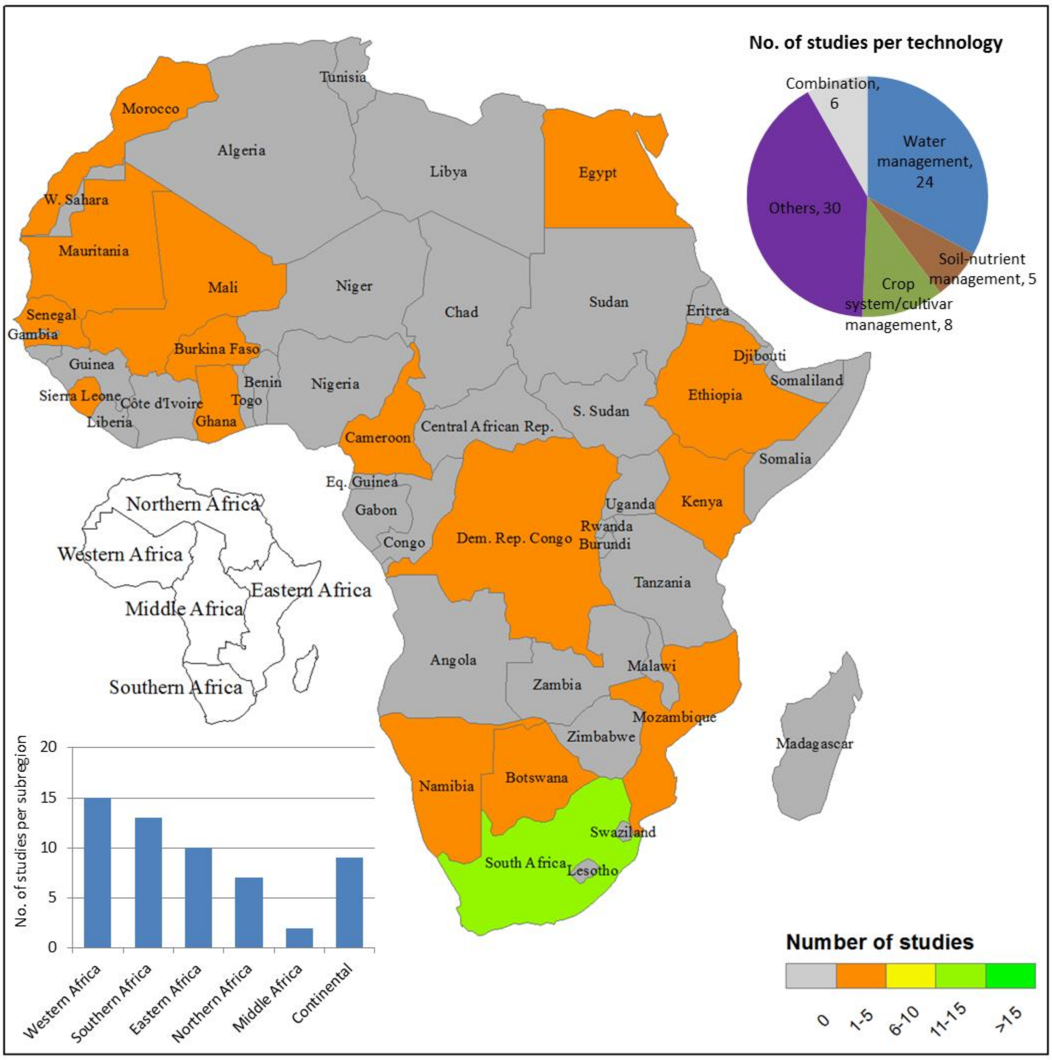

Figure 20: Review results: Number of agro-economic modelling studies with focus on higher aggregation level per country and subregion

As mentioned above, agro-ecosystems modelling was not required to occur as part of the economic modelling study because only a few of studies were using an integrated approach. In most cases, the study represented economic *ex ante* modelling of ag-TI or provided results that represented impacts of (for instance) climate change in different socio-economic groups, regions or farming systems. In a few studies the analysis was quite generic and therefore farming systems analysis approach was somewhat vague.

In this review, computable general equilibrium models (CGE) were clearly the most common model type and CGE was used in 31 of 59 studies. A few global CGE analyses which highlight Africa are included here. Partial-equilibrium modeling was applied in 11 studies, systems simulation or agro-ecosystems modelling jointly with economic modelling in 11 studies, and other modelling methods in 11 studies. These numbers include six studies which applied multiple methods. Hence, most studies focused on national-level issues as an economy-wide CGE analysis was so common. This focus may be partly due to our search term not capturing properly studies of lower-level aggregation. However, CGE models are well-suited to situations where studied industry represents an important share of national economy. As agriculture is a major industry in developing countries, CGE may be a natural starting point in many cases. Partial-equilibrium (i.e. sector-specific) studies and studies applying systems simulation or joint bio-economic modelling were substantially more detailed than CGE analyses.

A set of studies were classified as integrated agro-economic modeling studies based on their modeling approach. Besides an economic modeling component, these studies either had a modeling component describing biological or agro-ecological processes or a component utilizing the results of biological or agro-ecological models. In some cases, the component was quite simple one, for instance, based on the use of a production functions.

To provide two examples on these models, Valderrama et al. (2011) deals with the assessment of sustainability in the exploitation of groundwater by agriculture in arid and semi-arid lands. They use equations to represent water stocks and the use of irrigation water in agriculture, and link them to farms' gross margins in two regions. Hence, "higher aggregation" in this study mainly refers to the regional aspects related to water management. By contrast, Tengbe (2001) use a natural resource management model which is able to capture the economic, social and ecological variables that influence resource management. The paper describes three submodels: an ecological model, an economic model and a social model, which all interact. The model for instance determines the impact of shifting cultivation methods on vegetation cover, and the relationship between the mineral produced through open cast mining and the vegetated land destroyed to achieve this, and links these to GDP. Topic-wise the most common issue of interest in the reviewed studies was related to water management (Table 7). Water management practices were considered in 40% of reviewed studies. In particular, these studies elaborate the role of irrigation in agriculture. Climate change as an issue was also frequently in the focus. Water issue was a common topic also in studies which were excluded from the analysis.

Table 7: Reviewed agro-economic modelling studies with focus on higher aggregation level by topic

Topic	Number of studies
Water management	24
Nutrient management	5
Crop system or cultivar management	8
Land use	8
Other	22
Mixture	6

Nutrient management, typically referring to improved fertilizer applications, was examined in five studies. Crop cultivar choice and management, including the use of GM technologies to improve productivity, and land use, which usually referred to the allocation of land to different agricultural production activities, was of interest in altogether 16 studies. These are quite convenient starting points because economic analysis by definition focuses on the allocation of resources. At least six studies considered multiple resource management issues.

The category "other" received almost as many entries as water management. There were several studies analyzing various technologies or technological change in agriculture at a quite generic level, as well as studies analyzing issues such as pest control, joint livestock-pasture management, cultivation technologies, the role of extension and infrastructures or investments in general.

Several studies considered multiple farming systems by definition because they were economy-wide analyses. However, the level of farming system details included in these studies was very low. Irrigated (dryland) systems were considered in almost half of the studies. Regarding other studies, at least agropastoral and pastoral systems, humid lowland tree crop systems, maize and cereal systems were considered.

3.4.2 Conclusion

At higher level of aggregation, water management issues are a well-studied topic. Land use is also addressed in many studies. By contrast, other management issues and system comparisons are less well studied. The level of detail in studies at higher level of aggregation is very low. Hence, these studies are hardly ever explicitly integrated to agro-ecosystem models. Sectoral or system-specific analyses provide richer setup than economy-wide analyses because sector or system-specific models can include more detailed information about the production system. Due to the lack of (reported) details, studies at the higher aggregation levels tend to focus on broader issues such as water resources management, technological change (generic) or land use at large, and particularly on policy-level issues.

4 Generalized findings regarding potential impact of the various technological innovations

4.1 Innovations related to water management

Climate change and rainfall variability affect the livelihood of smallholders' farmers in Africa. The study by Wossen et al. (2014) showed that severe dry spells could reduce total production by 40% and increase poverty rate by 10% in northern Ghana. Hence, innovations related to water management are important climate change adaptation strategies for small-scale farmers. In this review, only a small fraction of the papers (10%) was found having a focus on the potential impact of water management innovations on farmers' livelihood and the environment.

Most of the agricultural economic models (AEMs) identified in this review showed that an increase in water availability positively affects the welfare and food security of smallholder farmers. In Ghana, the introduction of irrigation could raise farmers' income between 96% and 107% (Wossen and Berger, 2015). In Burkina Faso the income increment is more modest and is between 17 and 21% (Sanfo and Gérard, 2012). Wossen and Berger (2015) have also shown that irrigation technologies can reduce poverty rate by 20 to 30% and increase farmer's household food energy consumption by 75 to 81%.

In terms of environmental impact of irrigation, the AEMs predict mixed results. Belhouchette et al. (2012) showed that increasing water availability in Tunisia will potentially result in win-win situations; 45% increase in farm income and substantial reductions regarding salt accumulation and nitrate leaching. On the contrary the AEM developed by Jeder et al. (2011) showed that in the context of unsustainable use of irrigation water in water stressed areas in Tunisia, an increase in water price of 13% would decrease water consumption by 14 to 65% and soil erosion between 3% and 7% but reduce farmers' income by 6 to 24%.

Summarizing these ex-ante impact assessments, innovations related to water management can have positive outcomes on farmers' welfare and food security in West and Northern Africa. The environmental implications of these innovations are not clear-cut. Further research is therefore needed on this issue.

4.2 Innovations related to soil nutrient management

A substantial number of the agricultural economics models (AEMs) identified in this review (58%) focused on soil nutrient management and conservation. Three types of soil nutrient management technology are assessed: the use of mineral fertilizer, organic fertilizer and the introduction of leguminous crops in the cropping system. Improving soil nutrient content is critical for the sustainability of agriculture in most parts of Africa. In an explorative study, Tittonell et al. (2009) have shown that without the adoption of improved soil nutrient management technologies farmers might be able to be food self-sufficient in 70% of the cases but will be mining soil organic carbon at a rate of 0.28-1.61% per growing season.

Introducing soil nutrient management innovations potentially improves income, food security and soil fertility. Using AEM, Bidogeza et al. (2015a,b) showed that the adoption of green manure (Tithonia diversifolia) and chemical fertilizer (DAP = Di-Ammonium phosphate) would potentially improve simultaneously food production, income and soil organic carbon in Rwanda. The same outcomes have been predicted by two other AEMs. In Kenya, Valdivia et al. (2012) found that by increasing fertilizer availability (50% price reduction) to smallholder farmers, the poverty rate is likely to drop by 1.3% soil nutrient depletion by 26.2%. In Zimbabwe, Tittonell et al. (2009) using AEM showed that an increase in the application of nitrogen (50 kg/ha/season) and phosphorus fertilizer (12 kg/ha/season) is necessary to achieve food self sufficiency and a positive soil organic carbon balance. Finally the AEM by Franke et al. (2014) indicates that combining grain legumes with mineral fertilizer application could simultaneously increase soil carbon content and farmers' income in Malawi.

Soil nutrient management technologies can result in trade-offs between economic and environmental outcomes. The AEM developed by Schreinemachers et al. (2007) showed that in Uganda, increased use of fertilizers did not improve the stock of nitrogen in the soil and even though it improved substantially the welfare of farmers, the poverty rate remained high. The same outcome has been predicted by Woelcke (2006) who showed that sustainable agricultural intensification is not possible under the current market conditions - even when technical and capital constraints are relaxed. In this Ugandan case study, it was predicted that the adoption of integrated nutrient management using organic and mineral fertilizers coupled with improved access to credit, induced an increase in farm-household income between 4% and 9% but resulted a higher soil nutrient depletion with respect to nitrogen and potassium (ibid). Even when the AEM is constrained to result in positive soil nutrient balances of N, P and K, no feasible solutions were found except for commercial farmers; however their income was predicted to shrink by 30% on average. Hence, there seems to be a trade-off between farmer's income and soil nutrient depletion.

Regarding soil conservation technologies, agricultural economic models (AEMs) predict mixed results on the impact of these technologies on farmers' welfare and the environment. In Tunisia, a compulsory adoption of reduced tillage and legume-based crop rotation combined with the avoidance of bare fallow was predicted to result in a trade-off between soil erosion and income (Louhichi et al., 2010). Depending on the farm resource endowment, the geographic location and the specific climatic conditions, reducing soil erosion by 7.5% to 32.5% was associated with a reduction of farmers' income by 4% to 40%. Using the same AEM, it was also predicted that the adoption of an anti-erosive technique (1.5 m sand barrier built along contour lines and generally reinforced with cactus and olive trees) led to a synergetic increase in farmers' income and reduction in soil erosion (ibid). Similar outcomes have been generated by the AEM developed by Tré and Lowenberg-Deboer (2005), applied in Nigeria for assessing the potential impact of alternative mulch-based management systems on maintaining soil fertility. The model predicts that alley cropping with natural bush increases farmer's net return by 72-154% while maintaining soil organic matter and potassium content at a positive balance. However they point out the critical role of capital availability and secure land title for the adoption of mulch-based technologies for plantain production systems (ibid). Related to this, the AEM by Shiferaw et al. (2014) predicted that cross-compliance policies which link farmers' access to vital input (e.g irrigation water) or farm program benefits to conservation objectives can substantially increase the adoption rate of soil conservation practices by farmers.

4.3 Innovations related to crop system/cultivar management

A substantial number of the papers identified in this review (55%) assessed potential impact of innovations related to crop systems. The AEMs that were applied assessed the potential impact of improved crop varieties and/or, changes of the crop species – often in conjunction with changes in planting dates - or the sequence of crops in cropping and crop-livestock systems[5]. Improved crop varieties may imply varieties with a higher yield potential or with higher tolerance to abiotic and/or biotic stresses. Using improved varieties is predicted to increase farmers' income and food security status. In Sierra-Leone, the provision of a fully subsidized high yielding rice variety is expected to increase rice production by 100%, rice consumption by 30% and farmers' income by 109% (Louhichi and Gomez y Paloma, 2014). Drought resistant and virus free sweet potato varieties are predicted to improve small-scale farmer's food security in Uganda (Ilukor et al., 2014). In Ghana the adoption of early maturing varieties potentially increases bean and groundnuts yield by 80% and 32%, respectively, and improves farmers' income and food security status (Wossen et al., 2014). Finally a 10% increase in productivity via farmer-to-farmer exchange of improved banana planting materials and recommended management practices is expected to reduce poverty rate by 21% and poverty gap by 12.2% (Komarek, 2010).

The potential impacts of changes in crop /cropping system on farmers' welfare and the environment are in general positive. Reduction of fallow period or improved fallowing by the introduction of leguminous plants has a positive effect on farmer's income. In Sierra Leone, the reduction of fallow period from 5 to 3 years coupled with a fully subsidized improved rice variety is predicted to increase rice production by 120%, rice consumption by 40%, and farmers' income by 136% and reduce poverty rate by 65% (Louhichi and Gomez y Paloma, 2014). Additionally, reducing bush fallow periods with sown leguminous plants

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[5] Note that 66% of the studies assessing innovations related to crop system/cultivar management have simultaneously assessed innovations related to soil nutrient management.

(Callopogonium mucunoides) in rotation with rice in Ghana, potentially increases cultivated rice area by 45%, farm gross income by 34% and farmer livestock asset (Yiridoe et al., 2006).

Diversification strategies with respect to cropping and farming systems were also predicted to positively affect farmers' income. Waithaka et al. (2006) predicted that cash crops (napier grass, tea and vegetable) are critical for large size households that depend largely on agriculture to increase their income. From an exploratory study in Kenya, the AEM by Herrero et al. (2014) predicted that in the context of decreasing farm size and increasing labor costs, diversification with cash crops is a key intensification strategy to raise farmers' income. Their AEM also predicted that dairy expansion is a promising option – but most viable when available land is not a constraint (ibid).

The study by Komarek (2010) found that the diversification of current the production system with vanilla crop is expected to increase household welfare by 16% while maintaining food security in Uganda. But note that most of these outcomes are only possible if there is a functioning credit market and output quality improvement to reduce farmers' liquidity constraint and lift farm-gate vanilla prices respectively (ibid).

Crop diversification can also improve soil fertility and conservation. In this respect, the AEM by Alary et al. (2007) predicts that it is possible to reduce land degradation by introducing spineless cactus, a perennial crop in Tunisian farmers' production systems. The adoption of spineless cactus will potentially increase the average stock of small livestock (Ewe) by 6% due to a reduction of the farmers' constraint on feed supply, increase farmer cash flow by 7% and reduce cereal production on marginal land by 21%. Similar results were obtained for banana cropping systems in Nigeria (Tré and Lowenberg-Deboer, 2005). The AEM predicted that alley cropping with Dactyladenia barteri and natural bush increases farmers' net return by 154% and 72%, respectively, and is more effective than cut-and-carry techniques with Pennisetum purpureum (ibid). These technologies maintained soil organic matter and potassium content at a positive balance (ibid). But capital availability and secure land titles are critical pre-conditions for the adoption of these mulch-based technologies in banana production systems (ibid). Related to anticipated climate change, one study indicated that shifting planting dates is a promising adaptation strategy that can reduce the poverty rate between 48% and 91% in Northern Ghana (Wossen et al., 2014).

Finally, the predicted impact of improved or more diversified crop-livestock systems is mixed. Tittonell et al. (2009) predicted a potential trade-off between food self-sufficiency and soil fertility due to structural changes in cropping and livestock sub-systems in Kenya. They showed that an increase in farmers' cultivated area under napier grass from 20% to 40% and reducing area of other food crops will potentially increase primary productivity by 1 t/ha/season, milk production by 45 liters/season and 156 liters/season, respectively, increase soil organic carbon and decrease food self-sufficiency for small and medium size farmers. Replacing less productive local zebu by cross-bred dairy cattle will potentially further increase the primary productivity and reduce the trade-off between food self-sufficiency and increase in soil organic carbon (ibid). The trade-off between soil fertility and farmers income in integrated crop-livestock systems was already shown in two early case studies in Mali by Dalton and Masters (1998) and Kuyvenhoven et al. (1998).

All these studies have pointed to the importance of policy interventions for effectively supporting the adoption of sustainable technologies even in situations with full access to information on these technologies.

4.4 Innovations related to mechanization

In this review, few papers (7.5%) have assessed the potential impact of mechanization on farmers' welfare. However, mechanization is increasingly important for smallholder farmers, especially in the context of increasing off-farm opportunities in rural areas. Takeshima and Nkonya (2014), for instance, predicted that small-scale farmers in Nigeria have a high willingness to pay for mechanized land preparation services, even when the price of the service is raised from 100 USD/ha (current cost) to 200 USD/ha.

Most of the studies predicted that mechanization technologies with tractor and animal traction increase farmer income and productivity. Tiberti and Tiberti (2015) showed that a hypothetical 10% increase in the use of oxen-ploughs in Tanzania would reduce the incidence of poverty by 7% and the poverty gap by 8%. A similar result has been predicted by a case study in Burkina-Faso. Sanfo and Gérard (2012) showed that introducing animal traction increases the very poor farmers' income by 34%, the poor farmers' income by 49% and maintain the income level of the less poor farmers. They further predicted that promoting access to farm equipment such as animal traction benefited the very poorest (ibid). The potential economic impact of mechanization is, however, modest for the Nigerian case study where introducing of land preparation with mechanization by tractor increases the income of small-scale farmers by 3% (Takeshima and Nkonya, 2014). However, they showed that the introduction of mechanization increased the production of labor-intensive crops such as yam by 66%; and it reduced total cultivated areas by 28% which would allow participation of farm-household in off-farm activities. Overall, these studies showed that mechanization through animal traction and use of tractors are beneficial for farmers' incomes and welfare. But none of the studies showed the impact of farm mechanization on the environment. This should be a topic for further research.

The study locations identified from literature search on bio-economic modelling studies at farm level summarized in this chapter are presented in Fig. 21 together with the locations of selected case studies (as described in Chapter 5) and the Green Innovation Centers of the PARI project and their target regions.

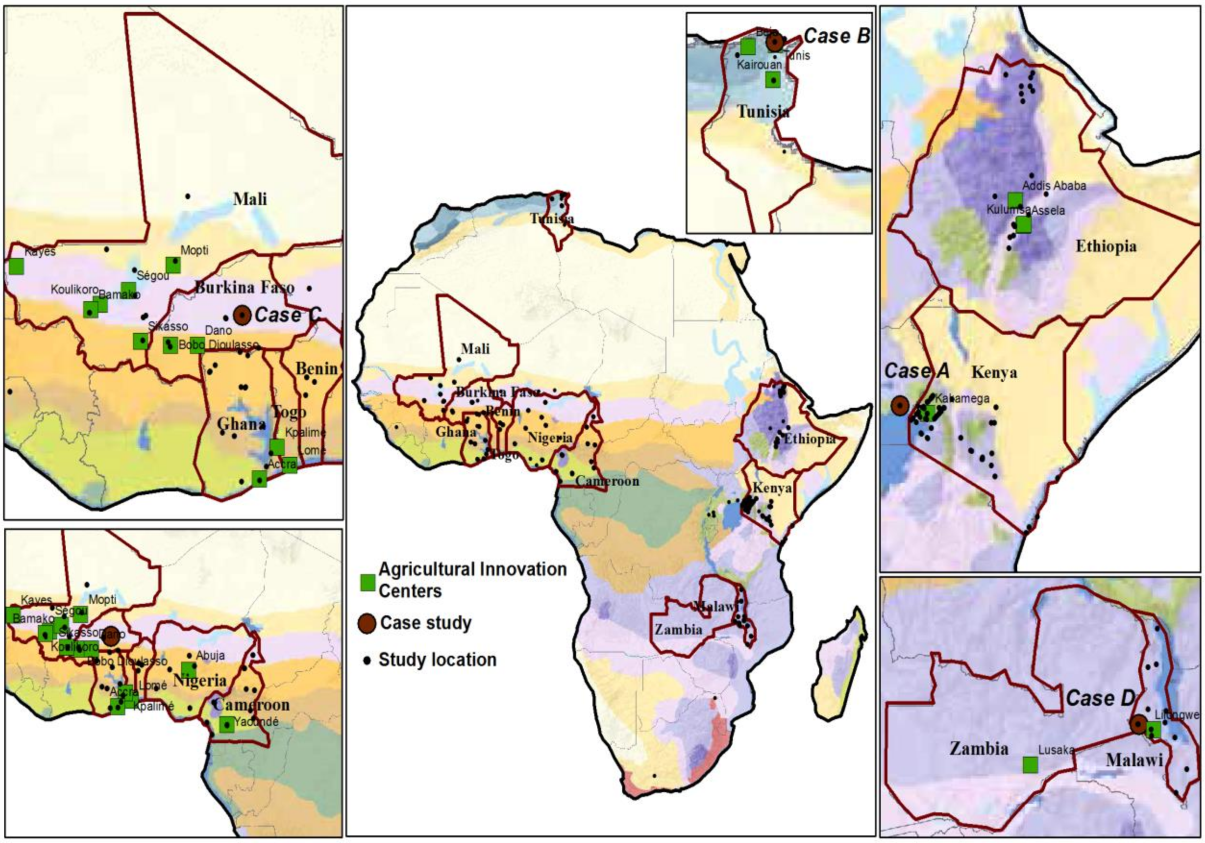

Figure 21: Location of Green Innovation Centers and their target regions

Note: Study locations identified from literature search on bio-economic modelling at farm scale and location of selected case studies presented in chapter 5 of this report superimposed on farming systems map.

Source: based on Dixon et al. (2014); for legend see Fig.3.

5 Generic modelling framework and selected case studies

5.1 Generic modelling framework

This section synthesises the lessons learned from our review into what we consider an ideal modelling framework for multi-scale ex ante evaluation of technological innovations in Africa. As shown throughout sections 3 and 4, the agricultural system models reviewed are in principle capable of quantifying important environmental and economic performance indicators of alternative technologies and their variability under current and future conditions. However, we noticed that the agricultural systems modelling studies reviewed did not systematically integrate biophysical and economic models across multiple scales, and did not explicitly integrate uncertainties related to ongoing and expected global change. To address these limitations, we propose a generic multi-scale integrated modelling framework that can be applied in the future to assess the potential impact of agro-technologies in a context of changes in climatic, socio-economic and demographic conditions for Africa. This proposed generic modelling framework is highly inspired by the work of Reidsma et al., (2015) carried out in the framework of AgriAdapt, a collaborative research project under the Dutch climate change programme (Wolf et al., 2012). It complies with the desirable quality criteria suggested in some recent papers on standards for “integrated regional assessments” (Antle et al., 2015; Reidsma et al., 2015), that is: having integrated biophysical and agro-economic components of modelling ag-Tis, having considered more than one scale of analysis (multi-scale, e.g. farm and region), and having included, at least, links to some platforms of innovation partners (transdisciplinary approach). Fig.22 below illustrates the potential application of this framework at national and sub-national level for African countries.

At the national level, scenarios on climate change and technological development feed biophysical models, which include crop models, greenhouse gas emissions models, leaching models, etc. These biophysical models should mainly focus on major crops and livestock produced in the selected African country that is object of analysis. At this level, boundary conditions are determined by an explicit consideration of agro-ecological zones, which allows identifying among others the distribution of different land suitabilities.

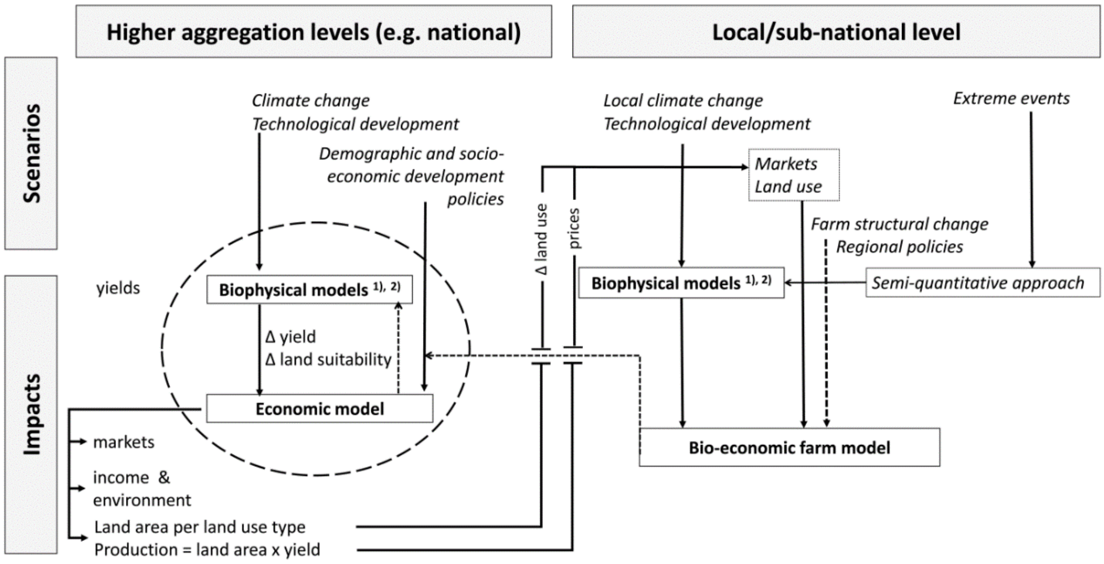

Figure 22: Generic framework for multi-scaling modelling of technological innovations in agriculture

Note: Agro-ecological zones and/or farming systems zones may be used to delineate simulation units for biophysical modelling – 1. Biophysical models comprise mainly crop models (process-based as well as empirical statistical models), livestock models and models on estimating specific environmental impacts of the agricultural production process 2. Another application type of biophysical modelling focuses on spatially assessing land suitability for different agricultural production activities – these can be conventional semi-quantitative land evaluation tools, or simple biophysical models for land resources assessment (e.g. AEZ method by Fischer et al. 2005).

Sources: Modified from Reidsma et al., 2015, published under Creative Commons Attribution 3.0 Unported (CC-BY) license.

Uncertainty in climate change impact projections at the national and sub-national level could be dealt with by utilizing results from recent work led by IFPRI on a comprehensive characterization of expected climate change effects on crop production potential up to 2050, which covers three major parts for East, West and Southern Africa and are disaggregated at country level (Hachigonta et al., 2013; Jalloh et al. 2013; Waithaka et al., 2013). Another comprehensive Africa-wide study performed by PIK- CCAFS/CLIMAFRICA (BMBF), which examined multi-sector risk hotspots (Müller et al., 2014), could provide information on hotspots of climate change up to 2080s and is equally useful to set boundary conditions and integrate uncertainty in the output of the biophysical models at higher and lower aggregation level.

Once alternative technological development and uncertainty related to climate change are introduced in biophysical models at higher aggregation level, resulting changes in crop yields can be fed into a nationally representative market model that, in addition, is driven by projections of population and economic growth. The market model generates information on food supply and demand in the form of change in land use and prices. That information sets the boundary conditions for the local (sub-national) analyses.

At the local/sub-national scale biophysical models are applied to assess the effects of technological innovations on major crops and livestock productivity. However, at this level scientific research methods should be complemented with transdisciplinary approaches utilizing the knowledge and experience of local stakeholders. For instance, the relatively limited capability of current crop models to deal with impact of weather extremes at local level should be complemented by semi-quantitative approaches that draw on stakeholder consultations to estimate potential productivity losses. At this level, joint stakeholder-scientist workshops can be organized to identify different extreme events, their likely future frequency, and the effect of associated counteractive measures, for example water management related technologies, pest control, or soil fertility management techniques. Together with information from the sub-national market model, assumptions on policies and farm structural change, this information enters a bio-economic farm model – conceptualized for different farm types within different farming systems (e.g. Van den Berg et al., 2007).

Feedback effects can be allowed between the bio-economic farm household models developed at local and sub-national level and market models at the national scale. Such linkages to the aggregate market model would work via the supply and environmental impact side. Aggregated results from detailed farm-level analysis from various regions at (sub-) national level can then provide information of total food supply and environmental impact that can be used to update scenarios for large areas and estimate changes in food supply and environmental impacts (here: at the national level). Such updated information can then - in a next iteration – be fed newly into sub-national/local modelling. We also found that explicit links between the multiple levels of modelling are often missing.

It should be borne in mind that such multi-scale iterative modelling requires consistency in scenario formulation on climate change, technological change and socio-economic development. For agriculture such consistent scenarios are called Representative Agricultural Pathways (RAPs) (Valdivia et al., 2015), currently developed world-wide. To this end, the AgMIP project (www.agmip.org; Rosenzweig & Hillel, 2015) collaborates closely with the various regional partners and/or other multi-institutional regional teams – e.g. for East, West and Southern Africa (Kihara et al., 2015).

5.2 Selected case studies

This section presents the four case studies from the review which best link to our framework, the PARI focal countries, and the type of technological innovations proposed by the Green Innovation Centers (GICs) programme in Africa proposed by the PARI project (status of implementation: October 2015; see, http://research4agrinnovation.org/). We only considered studies that are sufficiently transparent in describing their methodology. All selected studies integrate biophysical and agro-economic modelling for ex-ante evaluation of technological innovations for the agriculture and food sector (ag-TIs). Yet they do not fully comply with the other requirements of our framework: covering multiple scales and involving stakeholders in the definition of the study set-up (alternative options to be analysed) or the identification of promising candidate technologies.

In sections 5.2.1 to 5.2.4 we present the selected case studies. The findings from these case studies are not presented here as they have already been described and integrated in chapter 4. Here we focus explicitly on how the case studies relate to the structure and various elements of the modelling framework (Fig. 22). Interestingly, not one of the studies describes stakeholder engagement. Yet their methodologies provide thought-provoking and diverse examples of the integration of the various modelling components of our framework.

5.2.1 Case A - Technological and policy options for sustainable agricultural intensification in Uganda/Eastern Africa (Woelcke, 2006)

The model applied in this paper represents quite explicitly the structure of the right hand side of the generic modelling framework presented in Fig. 22 with a clear integration of a biophysical and economic model at sub-national level; here the district of Iganga in Eastern Uganda. The paper explicitly shows how to assess the impact of agricultural intensification technologies on smallholder farmers' income and soil nutrient balances. The agricultural intensification technologies assessed are integrated soil nutrient management practices, combining application of organic fertilizer (green manure and farmyard manure) and mineral fertilizer (diverse types of nitrogen, phosphorus and potassium fertilizer).

The bio-economic model used in this study comprises three components:

(i) The first component is a crop production module that uses artificial neural networks (ANN) to estimate different yield indices (crop yield, grain yield, stover yield) based on the International Center for Tropical Agriculture's on-farm trial data. The ANN explained on average 75% of the observed variation of yield indices.

(ii) The second component is an environmental module that estimates nutrient balances for nitrogen (N), phosphorus (P), and potassium (K) as proxies for indicating the relative environmental sustainability of the new technology. This module consists of a programming matrix that allows assessing nutrient losses and gains. The authors have used a combination of secondary and primary data to calibrate this environmental module.

(iii) The third component is a set of mathematical programming models that represents each of the four representative farm-household types' decision-making processes under a specific set of constraints. The four types of farm-household are subsistence, semi-subsistence, commercial and innovative farmers and have been identified in the study area via principal component and cluster analysis of field survey data.

The mathematical programming models maximize farm-household income subject to consumption, financial, technical, and environmental constraints. Each mathematical programming model represents a specific farm-household type and is a mixed integer linear programming model of 507 variables and 201 constraints. The calibration of the mathematical programming models is described explicitly in the paper and was based on detailed data collected on the different type of farm-household identified in the study area. The calibrated model has shown a very high goodness-of-fit (R^2 is between 0.89 to 0.99) because it was calibrated on observed area under various crops for each of the farm-household types.

The model developed in this paper is neither dynamic nor recursive and does not take into account production risk and farmers risk aversion behaviour, critical component of the generic modelling framework presented above. These factors are quite important for simulating farmers' decision-making over time and allowing feedback effects of soil nutrient depletion on future production. Bidogeza et al. (2015) and Wossen et al. (2014) provide good examples of the integration of farmer risk aversion behaviour and daily rainfall variability into agricultural economic models. Van Wijk et al. (2009) provide a simulation model (NUANCES-FARSIM) that allows feedback effect of soil nutrient depletion on crop yield; but the integration with a mathematical programming model has not been performed.

5.2.2 Case B - Sustainability of irrigated farming systems in Tunisia/Northern Africa (Belhouchette et al, 2012)

This case study follows up on the one described above and particularly illustrates the inclusion of extreme events (excess and low rainfall) in an integrated biophysical and economic optimisation approach at sub-national level. The approach allows assessing the impact of current cropping systems and water allocation on farmer income and environmental sustainability of irrigated areas in Tunisia. To avoid future land degradation, farmers should increase the amount of irrigation water applied to their crops in order to reduce soil salinization and nitrogen leaching risks. However, in the perspective of the farmers increasing irrigation water represents a trade-off between a short-term increase in production costs (reduction of income) versus long-term objectives to maintain soil fertility.

To deal with the highly variable rainfall and environmental problems, the authors employed a recursive stochastic programming (RSP) method instead of a stochastic dynamic programming approach to reduce the dimensionality of the problem and the computing time. The RSP consists of two modules: a biophysical model (CropSyst model) and a bio-economic farm model. The CropSyst model (Stöckle et al., 2003) is a cropping systems simulation model that simulates at the field level yield and environmental effects of specific cropping systems given information on soil and weather characteristics and previously grown crops. The CropSyst model includes a generic crop-growth simulator that can be calibrated for different annual field crops and varieties; it can also be used to simulate perennial crops and environmental indicators such as soil salinization. The CropSyst model generates technical production coefficients, which constitute the main linkage between the biophysical and the economic model (see, also Appendix to this report).

The bio-economic farm model is a dynamic optimization model, which maximizes the farmer's expected net present value subject to a set of constraints. It allows identifying which decisions are taken by the farmers over multiple years. The outcomes of one year constitute the input for next simulation year. The technical production coefficients (see, appendix 1 for elaborated examples) generated by the CropSyst model are represented in their primal forms within the economic model, directly relating cropping system to yield/biomass. The bio-economic farm model is solved recursively over a time period of 10 years divided in yearly time steps that consist of two decision steps representing the two growing seasons in a year. This bio-economic farm model has three sets of constraints. Land constraints ensure that the allocated areas do not exceed the available arable lands. Transfer constraints ensure that area allocated to a crop in a second decision step is equal to the area allocated to the crop in the first decision step (i.e. on the specific cropping sequence). Feed constraints allow equating the available forage resources to the potential demand of farm livestock unit. Rainfall has been modelled as three states of nature (low, medium and high) with given probability of occurrence within each growing season derived from a statistical frequency analysis approach.

The biophysical and bio-economic farm models are calibrated using experimental data and field survey data. Experimental data - yield and biomass for forage crops - are collected for the main crops studied. The experimental data on yield/biomass allows calibrating the radiation use efficiency and the biomass transpiration coefficient by minimizing the difference between simulated and observed yield/biomass. The relative root mean square error (RRMSE) value was used to assess the goodness of fit of the model. A RRMSE of 10% was considered as an acceptable level of calibration accuracy. The CropSyst model was successful at predicting yields and biomass of maize, barley, oats and berseem with the RRMSE lower than 10%. It was less successful at modelling wheat and sorghum forage crop – where the RRMSE was 13%; and it performed badly at predicting alfalfa crop yields with an RRMSE of 18%. Finally, the model successfully simulated soil water content with an RRMSE less than 10%, but was less accurate in simulating soil nitrogen dynamics and nitrate leaching losses (with RRMSEs varying between 25% and 54% depending on the soil type).

To calibrate the bio-economic models, field surveys coupled with farm level data are used to identify the different cropping systems, the different management strategies of farmers and the prices of input and outputs in the study areas. The bio-economic farm model was calibrated by comparing the model result with the one observed at the selected farm type. Two criteria were essentially used for that purpose: the surface area and yield of each group of crops and the capability of the model to reproduce the main farmers decisions when the rainfall changes. The calibration process has shown a relative good goodness of fit. The difference between observed and simulated values of percentage surface area was about 30% and the difference between observed and simulated yield was less than 15%.

This integrated bio-economic approach combines experimental, statistical and expert knowledge to gather sufficient data for the CropSyst and bio-economic farm models. Even though the models do not assess specifically a new type of ag-TI they can easily be adapted to do so. The main limitation of this combination of models is that it does not include the potential risk aversion behaviour of the farmers, which is an important parameter to integrate when studying farmers' decision-making under risk.

In terms of policy implications for sustainable management of irrigated farming systems this research highlights the potential negative long-term environmental impacts of irrigation water rationing in dryland areas.

5.2.3 Case C - Irrigation water and mechanization in Burkina-Faso/Western Africa (Sanfo & Gerard, 2012)

The paper describes the potential impact of rural policies on the behaviour and income of farm-households in the Plateau central area of Burkina-Faso. This case study provides an illustration of how technological development, regional policies and farm structural change can be modelled at sub-national level with a bio-economic farm model (see, right hand side of Fig. 22). Methodologically the paper explicitly integrates farm risk aversion behaviour, which was identified as the main weakness of the model presented in the case study B.

Five types of rural policies are assessed in this paper. The first two policies (1-2) are the development of public infrastructure such as an increase in irrigation water availability via the provision of small tanks to store rainwater, and a reduction in marketing costs via the construction of roads and collection and storage facilities for agricultural product. The next two policies (3-4) involve improving poor farmer access to capital. This is done via an improvement of their access to mechanization (animal traction) (3) and credit (4). The last type of rural policy (5) implies the stabilization of grain crops price (rice, maize, millet, sorghum) as a risk management strategy. The model developed takes into account production risks associated with the agro-climatic environment of the Plateau central area and the heterogeneity of farmers' initial conditions (in terms of resource endowments/ assets).

The model describes the farmer decision-making process with a non-linear mathematical programming model originally developed by Gérard and Marty (1997). The model is recursive and dynamic with a yearly static optimization as the one described in case study B; and the model parameters have been calibrated by reproducing past trends (period not specified in the paper) observed in the study area. The structure of the model involves the maximization of an objective function subject to a set of constraints. The objective function is a mean-variance utility function with endogenous risk aversion. Wealth is the sum of the monetary value of assets (equipment, livestock, cash and savings). Risk is represented in the objective function as half the product of the expected possible variance of wealth and the risk aversion coefficient of the farmer, which is endogenous to the model. Two types of constraint are integrated into this model: farm level and regional level constraints.

Farm level constraints ensure that resource allocation does not exceed total factor endowments in land, labour and capital. Natural resource use constraint take into account the volume of water available for agricultural production. The liquidity constraint ensures that the sum of total expenditures for production and family consumption, investments and savings does not exceed cash available in the previous year. Note that consumption includes school costs, minimum clothing, food expenditures and a consumption propensity parameter, which is a proportion of the expected profit. Finally a nutritional constraint allows consumption to be at least equal to a minimum calorie and protein needs.

Regional level constraints address different market imperfections. The capital market imperfection is represented by a liquidity constraint and maximum borrowing level for the whole region. Imperfect information on agricultural product markets is represented by two variables for prices: expected and real prices; production decisions are only based on expected prices, and real prices determine subsequent savings and consumption. Labour market imperfections are represented by an aggregate limited possibility of buying and selling farm labour. Also off-farm activities are restricted at the aggregate level. Several exogenous parameters are introduced in the model and allow the computation of a set of output variables. The exogenous parameters are factor prices, access to credit, interest rate, wage rate levels, off-farm activities opportunities and population growth. The output variables are the income of farm households and their sources, land allocation between various crops, techniques used, agricultural production, consumption expenditures and labour allocation among the various activities including off-farm activities.

The main limitation of this modelling study is that it lacks explicit representation of production activities with a biophysical model. This will likely limit its capacity to simulate the introduction of new crops or new farm technologies. The following cases study provides however an example of biophysical model that further integrates livestock activities and that can be useful to model smallholder farmers' decision making in an integrated crop-livestock production system.

5.2.4 Case D - Sustainable intensification with grain-legumes systems, Malawi/Eastern Africa (Franke et al., 2014)

This case study assesses the potential impact of technology development by introducing two types of grain legumes in a maize-based cropping system at sub-national level. Soil carbon content and farmer income are the main impact outcome assessed by the model. The methodological framework illustrates how with a few primary data one can integrate crop and livestock production in biophysical models – a feature not presented in the previous three cases studies.

The first step of the modelling framework consists of the identification and characterization of farm types based on a detailed survey of a sample of farmers and using information on biophysical and socio-economic variables. This detailed characterisation of the farm types allowed building the biophysical model.

The simulation model developed in this paper constructs virtual farms that represent each of the farm types. The model used is the NUANCES-FARSIM (nutrient use in animal and cropping systems: efficiencies and scales- farm simulator) developed by van Wijk et al. (2009). This is a dynamic model and allows performing exploratory analysis of strategic long-term management practices at the farm level. Four interrelated modules are included in this farm type simulation model: labour availability (NUANCES-LABOURSIM), crop and soil interaction (NUANCES-FIELD), livestock production (NUANCES-LIVSIM) and manure handling (NUANCES-HEAPSIM). Each module is composed of summary functions that have been identified from experimental research, mechanistic modelling and expert knowledge. Hence this method limits the need for input parameters that are hard to estimate in African settings. The model has an average goodness of fit at predicting groundnut and soybean yield variations (51-62%), but performs better at predicting maize yield variation (82%). The model simulations were run over a period of 20 years for each virtual farm type. The biophysical outputs of this model are then used in a cost benefit analysis to assess the profitability of alternative production scenarios.

The current model has the advantage of representing complex interactions between crop production, soil fertility and labour availability at the farm level with an explicit option of integrating livestock activities. It also allows to explicitly incorporate the impact of rainfall variability on yield. But it is limited by the fact that farmers risk aversions are not accounted for and other type of constraints, especially liquidity constraint are not explicitly integrated. However the biophysical outcomes of the model can constitute a more realistic input of integrated agricultural economic models that employ optimization models to describe farmer’s decision-making processes, especially in data scarce areas.

6 Conclusions

One of the critical challenges that Africa will face in the coming decades is to increase food production in a sustainable way in a context of future climate changes and a still strongly increasing population. The use of integrated (biophysical and agricultural economic) modelling to predict the potential impact of agricultural innovations is therefore critical, especially because farming systems in Africa are highly diverse – by far too diverse to be adequately investigated by experimentation. Furthermore, it is essential to consider information on future climate risks to food production in assessing agricultural innovations – and is even more difficult to gain such information from experimentation than for current known farming systems. Even for current climate, observed yield series over a sufficiently long number of years are usually not available for assessing such climate-induced risks reliably; biophysical modelling, however, can generate sufficiently long series on current and future climate-induced risks. Such information can in principle be integrated into agro-economic models for ex ante assessment of risks and opportunities for alternative agricultural innovations in different environments.

This report critically reviews the use of agricultural system modelling (ASM) at different scales over the period 1996 to 2015 for ex-ante evaluation of technological innovations in Africa. Three types of ASM have been assessed: biophysical models, agro-economic models at farm level, and agro-economic models at higher aggregation level. The ASMs identified in this review have been assessed on their capabilities, gaps and potential to inform decisions on investment in developing technologies and policies. In the following we summarize results for the key questions posed in the introductory chapter:

(1) *What type and how many ag-modelling studies on technological innovations (TIs) have been performed?*

In total, we identified 140 biophysical modelling studies, which have mostly assessed alternative cropping systems that were designed to make more efficient use of (soil) nutrients, water, and genetic resources. In terms of agro-technologies considered, the biophysical modelling studies have focused on improved crop management, combinations (i.e. agro-technology packages), soil nutrient management and conservation, water/soil moisture management, and other technologies such as mechanization or utilizing seasonal climate forecasting for tactical/strategic crop management adjustments.

Crop models applied were mostly representatives of the well-known and widely used crop simulation model families such as APSIM, CROPSYST, DSSAT and Wageningen SUCROS/ LINTUL types (Keating et al., 2003; Stöckle et al., 2003; Jones et al., 2003 and van Ittersum et al., 2003), which are process-based and work with a daily time step.

Most studies focused on the effects of technological innovations on productivity (sometimes yield stability) - and many were performed in a climate variability and climate change adaptation context. In terms of location, most of the biophysical modelling studies were found in East and West Africa, followed by Southern African countries. Finally, the majority of the studies were performed at "field scale". Good overviews on crop model applications for assessing climate change impacts and adaptation in Africa have been given earlier by Webber et al. (2014) and Roudier et al. (2011).

Agro-economic modelling (AEM) studies at farm level found relevant for our review amounted to 40 in total. Research groups with the highest number of authors originated from Wageningen University and Research Centre in The Netherlands, Hohenheim University in Germany, and the International livestock Research Institute (ILRI) in Kenya. The agro-economic models applied to assess technological innovations in Africa can be grouped in three broad types of models: mathematical-programming models, multi-agent system models and a combination of multi-agent system and mathematical-programming models.

More than half of the studies have explicitly taken the time dimension into account and used dynamic models; less than half have taken production and market risk into account – which appears to be a considerable short-coming. By far most studies assessed technological innovations at a local level. Few studies have been implemented at sub-national or national levels.

Most of the AEM studies at farm level focused, by order of importance, on Eastern Africa, Western Africa, Northern Africa, and Southern Africa. More than half of the studies identified targeted one (or more) of the twelve focal countries (i.e. with planned Green Innovation Centers (see, Fig. 21)). Kenya and Uganda have been the focus of most agro-economic modelling studies, followed by Tunisia and Ethiopia, Ghana and Mali.

The most frequently assessed technologies are those related to soil nutrient management and conservation and crop/cultivar management. A substantial number of these studies have assessed soil nutrient management and conservation in combination with crop/cultivar management practices, animal traction and/or water management. Few studies have focused on water management technologies. Finally, some other technologies or farm management practices and even investments in infrastructure have been assessed by the AEM studies. These include: mechanization by animal traction, the provision of seasonal climate forecasts to farmers, and the assessment of transport infrastructure.

Agro-economic modelling studies at higher aggregation levels amounted to 59. In these, the Republic of South Africa, Ethiopia, Ghana, Senegal and Morocco were the countries most frequently mentioned. Most studies performed national-level analysis including sector-specific analysis. There were few studies having supra-national (multi-country), continental or global focus (i.e. a global analysis providing results for Africa). Computable general equilibrium models (CGE) were the most common model type. Partial-equilibrium modelling, systems simulation or (partly) agro-ecosystems modelling jointly with economic modelling, was applied in fewer studies.

Topic-wise, these models focused on issues such as water management (irrigation in agriculture), land management, climate change, nutrient management and crop cultivar choice and management including GM technology. Most of them analysed economic issues at the regional level and assessed the impacts of (for instance) climate change in different socio-economic groups, regions or farming systems.

(2) *What are the outcomes - magnitude and type of effects of the TIs on sustainability/food security indicators?*

Looking at the outcomes from the biophysical ex ante evaluations, we find that many were mainly positive on effects of (mostly) “single conventional” agricultural technology innovations. For instance crop yield gains varied in most cases in the range of +5 to +20% as compared to current technologies.

Most of the agricultural technology innovations assessed by the agricultural economic models (AEM) at farm level report win-win outcomes for food security and income. The results are, however, rather balanced (plus/minus) for food-security and environment, income and environment, and food security, income and environment. This is indicative of the complexity to achieve both welfare and environmental goals.

Furthermore, several AEM studies show that an increase in water availability positively affects the welfare and food-security of smallholder farmers in West and North Africa. In terms of environmental impact of irrigation, the AEMs, however, come up with mixed results, which calls for further research on this issue. It was also shown that introducing soil nutrient management innovations potentially improve income, food security and soil fertility but can also lead to a trade-off between economic and environmental outcomes. Regarding soil conservation technologies, the AEMs predict mixed results on the impact on farmers’ welfare and the environment. For adoption of improved crop varieties we find that this will increase farmers’ income and food security status and that the potential impact of change in crop /cropping system including diversification strategies on farmers’ welfare and the environment are generally positive. Finally the predicted impact of improved crop-livestock systems shows mixed results. With respect to mechanization technologies with tractor and animal traction, we find that farmer income and productivity can be increased. None of the studies shows the impact of farm mechanization on the environment. Finally, the AEM studies reviewed suggest that a combination of different types of agricultural innovations could be very effective for sustainable agricultural intensification.

(3) *What are the gaps - and can they be bridged (target areas, technologies & weaknesses in the methodology)?*

The review of biophysical modelling studies reveals that the coverage of sub-regions and ag-TIs varies markedly. Looking in more detail at the twelve focal countries nothing or little was found for Togo, Zambia and Nigeria. Very few biophysical studies include also information on environmental impacts and profit, and there were just a few presenting multi-scale or higher scale analysis – which can introduce considerable bias in the results; most studies were restricted to local and regional scale. Finally, it appears that typical farming systems of semi-arid and sub-humid agro-ecological zones are better covered than other zones.

Also for the agro-economic modelling studies several gaps have been identified. In terms of area coverage, no relevant studies have been identified for Middle Africa. Not covered by AEM studies are also four focal countries of PARI: Benin, Togo, Cameroon and Zambia. In terms of technologies assessed, crop system and cultivar management has been assessed only in four out of the twelve focal countries –Burkina-Faso, Nigeria, Ethiopia and Kenya. Water management technologies have been assessed only in Tunisia, Burkina-Faso and Ghana. There are still many farming systems in the project focal countries that have not been covered by agro-economic models assessing innovations technologies.

Farming systems in Togo, Benin, Cameroon and Zambia are not covered at all by the studies identified. In Eastern Africa, the highland perennial, root and tuber crop, pastoral and irrigated farming systems have not been assessed. In western Africa, the root and tuber crop, humid lowland tree crop, pastoral and arid pastoral oasis farming systems have not been studied so far. In northern Africa and focal country Tunisia, there were no studies covering the arid pastoral and North African rainfed mixed farming systems.

Regarding the identified agro-economic models at higher aggregation level, many of them did not examine ag-TIs explicitly, but they examined innovations at a more general level or examined impacts of different shocks in the context of different production systems. For many African countries no publications were identified. Several studies considered multiple farming systems by definition because they are economy-wide analyses. However, the level of farming system details included in these studies is very low. Irrigated (dryland) systems are considered in almost half of the studies. Sectoral or system-specific analyses provide a richer setup than economy-wide analyses because sector or system-specific models can include more detailed information about the production systems.

A common gap is the relatively small amount of studies that incorporate information on risks specific to the cultivation environment-, e.g. on yield loss or crop failure, due to inter-annual climate variability and their impact on farmers' income and food security.

(4) *An additional, non-obligatory question was: What role can ag-models play in supporting future decisions on TIs / what is recommended on their use?*

Although a number of useful ex ante modelling studies on technological innovations have been performed – as documented in this report, there are also a number of serious gaps.

In response to the main gap, we already highlighted the need to develop a generic modelling framework for multi-scale *ex ante* evaluation of technological innovation in Africa that systematically integrates biophysical and economic models, across multiple scales and that would explicitly integrate uncertainties related to on-going and expected global change. We therefore proposed and presented a generic modelling framework - inspired by recent work of Reidsma et al. (2015) – and used selected case study examples to illustrate how its various elements can work (see, Chapter 5).

Furthermore the current huge efforts by networks like MACSUR and AgMIP should be mentioned aimed at improving biophysical and agro-economic modelling tools. These can feed and complement the modelling framework proposed in this report. For instance, progress has been made to better capture and quantify effects of extreme and adverse weather events and improve quantification of effects on the various environmental output variables (e.g. nitrate leaching, GHG emissions). In the studies reviewed in this report, the technological innovation packages analysed often reflect the still (limited) capability of the ex-ante evaluation tools.

Likewise, efforts are being made to better mimic decision behaviour at farm level. These positive developments hold promise for more useful future model applications in support of decision–making on investments in technological innovations and supportive policies.

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Supplementary Information (SI)

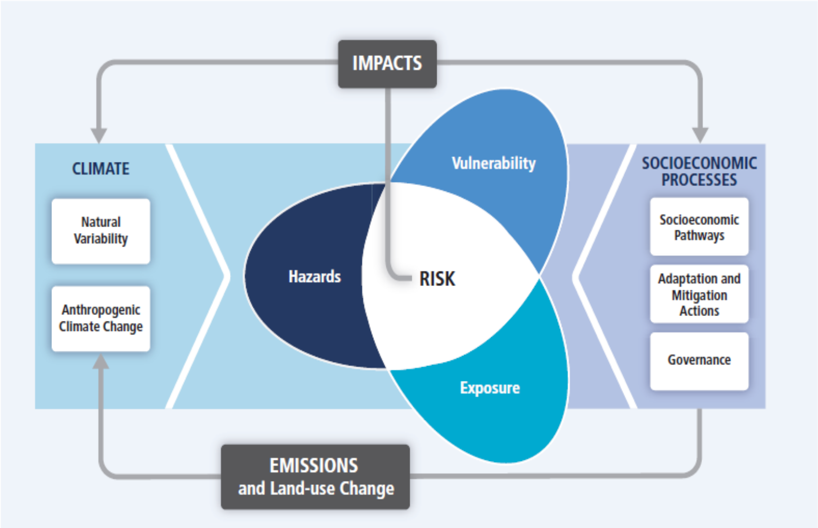

Figure S1: Illustration of the core concepts of WGII AR5.

Note: Risk of climate-related IMPACTS results from the interaction of climate-related hazards – with the vulnerability and exposure of human and natural systems.

Source: Modified from IPCC, 2014: Summary for policymakers. In: Climate Change 2014: Impacts, Adaptation, and Vulnerability. Part A: Global and Sectoral Aspects. Contribution of Working Group II to the Fifth Assessment Report of the Intergovernmental Panel on Climate Change, page 3. Cambridge University Press.

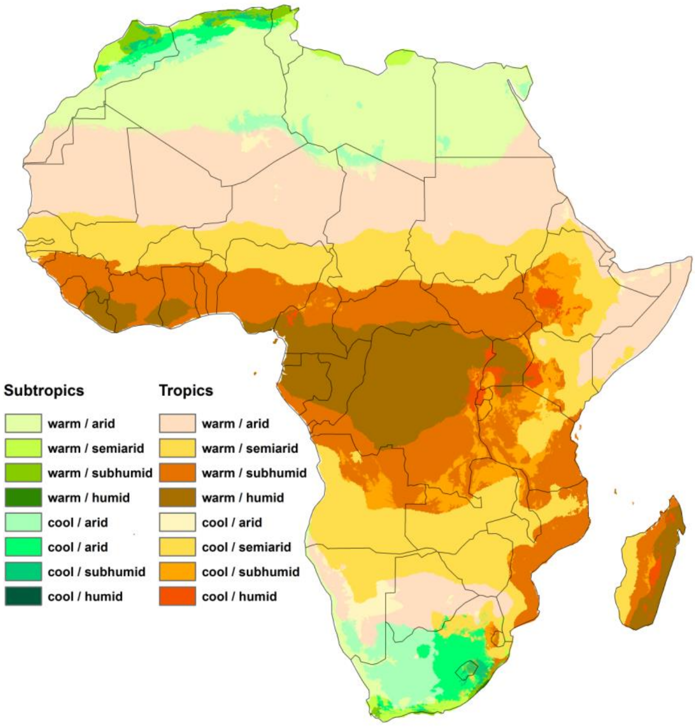

Figure S2: AEZs of Africa according to the *HarvestChoice* classification scheme

Source: Based on HarvestChoice, 2010. Agro-ecological Zones of sub-Saharan Africa. International Food Policy Research Institute, Washington, DC., and University of Minnesota, St. Paul, MN, published under Creative Commons Attribution 3.0 Unported (CC-BY) license. Available online from http://harvestchoice.org/node/8853.

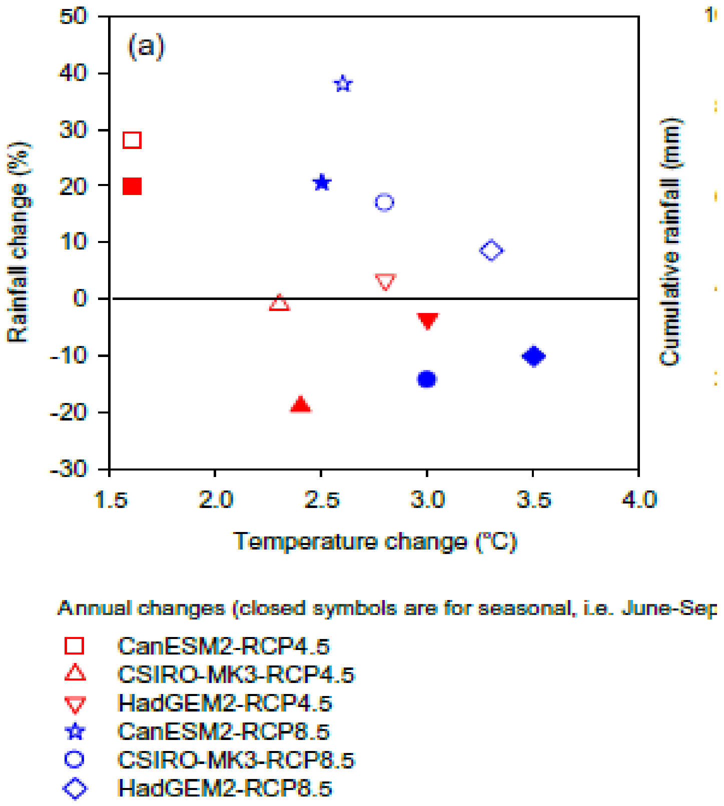

Figure S3: Changes in annual and seasonal rainfall and temperature as projected by different climate models in 2050s (2040–2069) relative to the base period (1980–2009) in the Central Rift Valley, Ethiopia.

Source: Reprinted from Climatic Change (129), Exploring climate change impacts and adaptation options for maize production in the Central Rift Valley of Ethiopia using different climate change scenarios and crop models, 2015, page 147, Kassie, B. T., Asseng, S., Rötter, R. P. Hengsdijk, H., Ruane, A. C., van Ittersum M. K., Copyright Springer Science+Business Media Dordecht (2015), with permission of Springer.

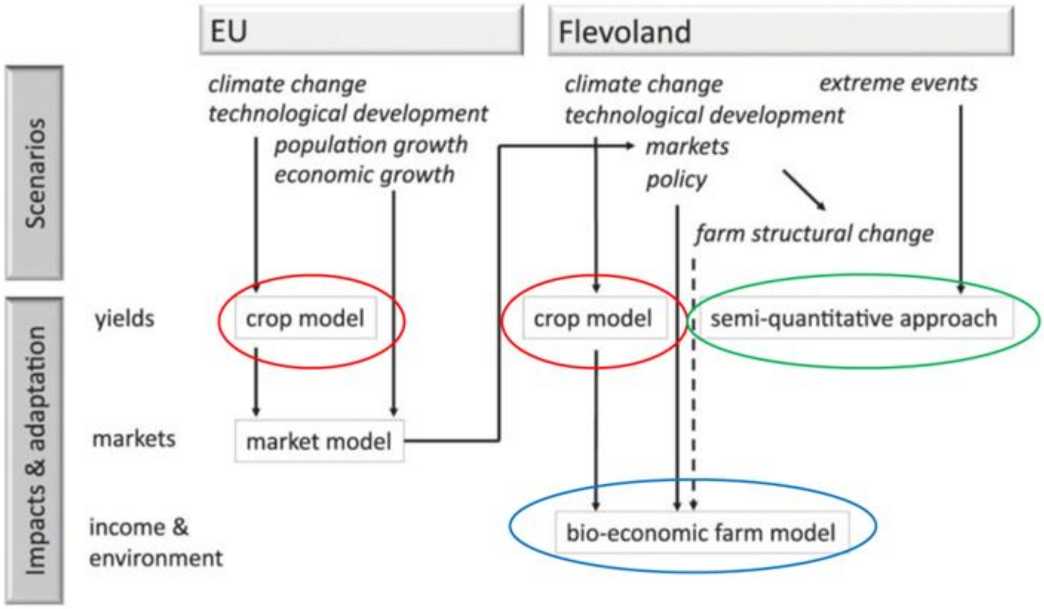

Figure S4: Multi-scale modelling of techno-innovations - an (almost ideal) framework from EU/NL including the drivers and methods used to assess impacts and adaptation

Source: adopted from Reidsma et al., 2015, published under Creative Commons Attribution 3.0 Unported (CC-BY) license.

Appendix[6]: Input-output coefficient generation by TechnoGIN for integrated agro-economic modelling – examples from Ghana

TechnoGIN, developed in the framework of the Systems Research Network for Ecoregional Land use planning (SysNet) project applies a target-oriented approach (Ponsioen et al., 2006). That, in first place mean, fine-tuning of (mixes of) inputs to realize a specified 'target' yield level under certain environmental and management conditions. Such approach enables us to quantify the required amount of various inputs such as labour, water, fertiliser, and their monetary values to attain target yield levels (e.g. as identified as desirable for narrowing yield gaps) in various land use systems.

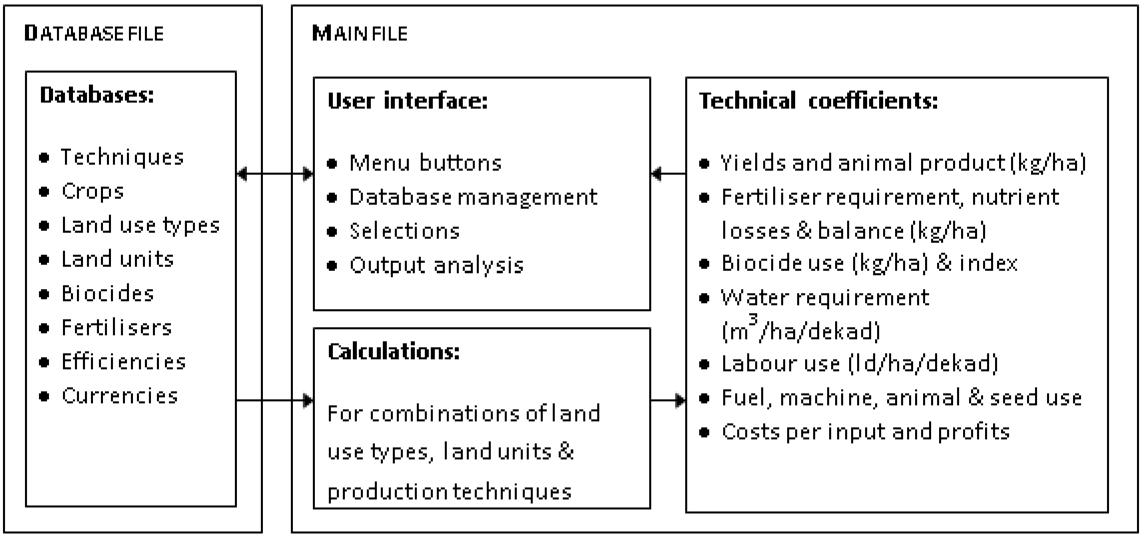

Figure 1: Simplified representation of the structure of TechnoGIN

Source: Ponsioen et al., 2006); the arrows represent flows of data

In this section, we present a few examples for Ghana, extracted from the detailed report by Wolf (2004) on related work from the VINVAL project[1].

For the pre-defined (estimated/simulated) 'target' yield levels, TechnoGIN calculates the technical coefficients (i.e. required inputs, environmental pollution) and hence, TechnoGIN may be applied for comparing resource use efficiency, labour demand, cost/benefit ratios and environmental pollution from different land use types and production techniques (Ponsioen et al., 2006).

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[6] Source: Wolf, J., 2004. Analysis of cropping systems in VINVAL case study areas. Results of TechnoGIN application to Ghana. Alterra Report, Wageningen, The Netherlands.

Main land use types and production techniques defined for Ghana case study, VINVAL project.

Land use types and production techniques defined for VINVAL case study are given in Tables 1 and 2.

Table 1: Land use types, start date of cropping season, and low (actual) and high (future) target yield levels as used in the analysis for the VINVAL case study areas in Ghana

Crop	Duration cropping season[1] (d)	Mean start land preparation / mean start crop emergence	Target yield[2] Low (ton/ha)	Target yield[2] High (ton/ha)
Cabbage	140	8 / 11	8	16
Cassava	360	8 / 11	12	24
Citrus	360	- / 1	7	14
Cocoa	360	- / 1	2.9	5.8
Cocoyam	290	8 / 11	10	20
Cowpea	140	8 / 11	0.4	0.8
Garden egg	140	8 / 11	3.8	7.6
Groundnut	140	8 / 11	1.1	2.2
Maize	140	8 / 11	1.5	3
Oil palm	360	- / 1	9.4	18.8
Okra	140	8 / 11	5.5	11
Onion	140	8 / 11	7.7	15.4
Pepper	140	8 / 11	0.6	1.2
Pine apple	360	- / 1	5.9	11.8
Plantain	360	- / 1	8	16
Rice	140	8 / 11	2	4
Tomato	140	8 / 11	7	14
Yam	290	8 / 11	10	20
Late Maize	140	21 / 24	1.5	3
Early Maize- late	140 - 140	8 / 11 – 23 / 26	1.3 - 1.3	2.6 – 2.6

[1] Season inclusive periods of land preparation and harvesting.

[2] Yield in airdry product.

Four different production techniques have been distinguished which are specified in Table 2:

A. Current (low) yield level with current system and actual fertiliser nutrient applications (nil at present);

B. Current (low) yield level with calculated fertiliser nutrient applications (indicated as future system for which site-specific nutrient demands and applications have been calculated);

C. Future (high) yield level with calculated fertiliser nutrient application (i.e. idem system B but high yield level);

D. Future (high) yield level with calculated fertiliser nutrient application and improved crop management and recovery of applied nutrients (i.e. idem system C but improved management).

Table 2: Main production techniques for actual and future cropping systems in the VINVAL case study areas in Ghana and their target yield levels and input use requirements

	Actual	Actual + calculated NPK	Future + calculated NPK	Improved future + calculated NPK
Technique	**A**	**B**	**C**	**D**
Yield level[1]	Low	Low	High	High
Recovery fr. applied N[2]	35.0%	35.0%	35.0%	45.5%
Recovery fr. applied P[2]	8.0%	8.0%	8.0%	10.4%
Recovery fr. applied K[2]	35.0%	35.0%	35.0%	45.5%
Relative labour input for crop	1.0	1.0	1.0	3.0
Relative biocide use[2]	1.0	1.0	1.0	2.0
Relative fuel use[2]	1.0	1.0	1.0	1.0
Relative machinery use[2]	1.0	1.0	1.0	1.0
Relative animal use[2]	1.0	1.0	1.0	1.0

1 Yield levels as specified in Wolf (2004, Table 1) for both low and high target levels for the different land use types.
2 See text above

The outputs of TechnoGIN are the technical coefficients that describe the input – output relationships of crop production systems (land use types with corresponding production techniques). The technical coefficients consist of:

a. evapo-transpiration and required irrigation water

b. N, P, K fertiliser requirements

c. labour demand

d. costs of fertiliser use

e. costs of biocide use

f. costs of other inputs (seed, machinery, animals, investments)

g. economic indicators

h. environmental impacts

Some results for a range of production activities and techniques considered in VINVAL

TechnoGIN calculates from the maximal evapotranspiration over the year for the specified land use types and from the annual rainfall distribution the required amount of irrigation water.

Results for different crops and production techniques for the VINVAL Ghana case study are shown in Table 3.

Table 3: Maximal evapo-transpiration (ET, in mm per year) and required amount of irrigation water (IRR, in mm per year) for the main land use types on moderately rich terrace soils in the VINVAL case study areas in Ghana with four production techniques.

Technique Crop	**A**: Actual	**B**: Actual + calculated NPK	**C**: Future + calculated NPK	**D**: Improved future + calculated NPK
	ET - IRR	ET - IRR	ET - IRR	ET - IRR
Cassava	993 - 43	993 - 43	1014 - 50	1014 - 50
Citrus	1108 - 25	1108 - 25	1108 - 25	1108 - 25
Cocoa	1108 - 25	1108 - 25	1158 - 33	1158 - 33
Cocoyam	799 - 0	799 - 0	818 - 0	818 - 0
Cowpea	454 - 0	454 - 0	454 - 0	454 - 0
Garden egg	454 - 0	454 - 0	454 - 0	454 - 0
Groundnut	454 - 0	454 - 0	455 - 0	455 - 0
Maize	454 - 0	454 - 0	454 - 0	454 - 0
Oil palm	1108 - 25	1108 - 25	1150 - 31	1150 - 31
Okra	454 - 0	454 - 0	457 - 0	457 - 0
Onion	454 - 0	454 - 0	459 - 0	459 - 0
Pepper	454 - 0	454 - 0	454 - 0	454 - 0
Pine apple	1108 - 25	1108 - 25	1108 - 25	1108 - 25
Plantain	1108 - 25	1108 - 25	1108 - 25	1108 - 25
Rice	454 - 0	454 - 0	454 - 0	454 - 0
Tomato	454 - 0	454 - 0	454 - 0	454 - 0
Yam	799 - 0	799 - 0	818 - 0	818 - 0
Late Maize	444 - 0	444 - 0	444 - 0	444 - 0
Early Maize- late Maize	651 - 0	651 - 0	651 - 0	651 - 0

Source: Wolf, 2004, p. 19

The nitrogen, phosphorus, and potassium balances have been calculated with TechnoGIN for maize cropping on moderately rich terrace and lowland soils with production techniques A, B, C and D. Techniques A and B result in the current low yield level, with respectively actual and calculated fertiliser nutrient applications. Techniques C and D represent more intensified systems with future high yields and calculated fertiliser nutrient applications. Technique D assumes improved crop management and recovery of applied fertiliser nutrients (resultsof TechnoGIN calculations are shown in Table 4).

For the specified target yield level, the crop's nutrient uptake is calculated with the QUEFTS approach (see, Ponsioen et al., 2006).

Table 4: Main nitrogen, phosphorus and potassium inputs and outputs (kg N, P and K per ha) for maize cropping on a moderately rich terrace soil with production techniques A, B, C and D and for maize cropping on a moderately rich lowland soil with production techniques B and D

Input/output	Techn. A Terrace	Techn. B Terrace	Techn. C Terrace	Techn. D Terrace	Techn. B Lowland	Techn. D Lowland
Crop N uptake	28	28	56	56	34	68
N losses[1]	9	9	50	32	8	43
N fertiliser[2]	0	0	62	44	0	60
Soil-N supply[3]	30	30	30	30	33	33
N-recycling[4]	7	7	15	15	9	17
P losses[1]	0	21	94	71	30	88
P fertiliser[2]	0	21	99	76	31	95
Soil P supply[3]	4	4	4	4	5	5
P recycling[4]	1	1	3	3	2	4
K losses[1]	35	35	30	30	38	32
K fertiliser[2]	0	0	0	0	0	0
Soil K supply[3]	40	40	40	40	44	44
K recycling[4]	12	12	26	26	15	30

[1] Losses through leaching, denitrification and volatilization for N, by fixation for P and by leaching and fixation for K.

[2] Amounts of fertiliser nutrients are based on actual applications for Technique A and are calculated from the nutrient demand for the specified target yield minus the natural nutrient supply divided by the recovery fraction of applied fertiliser nutrients (see, Wolf, 2004,full report) for Techniques B, C and D.

[3] Natural soil nutrient suppy is the overall results of nutrient input through precipitation, biological N fixation, N mineralization of soil organic matter, runon, and P and K mineralization as a result of weathering of soil minerals minus nutrient losses by runoff, fixation, leaching, etc.

[4] Recycling of nutrients through crop residues and manure.

Source: Wolf, 2004, p. 21