



Université de Montpellier

Ecole Doctorale GAIA

Sustainable intensification of smallholder farming systems for improved food security and adaptation to climate change in Africa

Gatien Falconnier

CIRAD

UR AïDA

Mémoire d'Habilitation à Diriger des Recherches

Montpellier

November 2024



" Je déclare avoir respecté, dans la conception et la rédaction de ce mémoire d'HDR, les valeurs et principes d'intégrité scientifique destinés à garantir le caractère honnête et scientifiquement rigoureux de tout travail de recherche, visés à l'article L.211-2 du Code de la recherche et énoncés par la Charte nationale de déontologie des métiers de la recherche et la Charte d'intégrité scientifique de l'Université de Montpellier. Je m'engage à les promouvoir dans le cadre de mes activités futures d'encadrement de recherche."

ACKNOWLEDGMENTS

There are numerous researchers, field assistants, project managers, colleagues and friends who played an instrumental role throughout my career path. I am grateful to Patrice Autfray who welcomed me in Mali during my first internship, and made me discover the realities of on-farm research in the tropics. With Jean-Claude Mouret at INRAE, I was able to pace up and down the rice paddy fields of Camargue and also learnt a lot on farmers' field monitoring – thanks Jean-Claude! My latter research experience at Icrisat-Mali would not have been possible without the constant support of Eva Weltzien and Fred Rattunde, I am grateful to them. I am also indebted to Peter Craufurd and Anthony Whitbread, who greatly facilitated the integration of my PhD study into the CGIAR 'Dryland Systems' Crp and were always supportive of the research I was conducting. Heartfelt thanks to partners at AMEDD, Bougouna Sogoba, Arouna Bakayoko and Ousmane Dembele, and at IER, Ousmane Sanogo, Salif Doumbia, N'Golo Coulibaly. Without your support, field work would have been impossible. I am also indebted to the field assistants for their contribution to critical data collection: Michel Sagara, Bakary Dao, Moumine Traore, Abdoulaye Dembele, Soungalo Bouare.

Tom Van Mourick supervised my PhD study while I was at ICRISAT. Thanks Tom for your guidance, and all the good fun in the field! I am profoundly grateful to Katrien Descheemaeker – whom I believe is the best supervisor one can find on planet earth. Katrien has this special ability to push you to achieve greater outcomes, without making you feel overwhelmed. I am of course immensely grateful to my PhD promotor Ken Giller. Ken has pushed me constantly to carry-out research that would eventually benefit the society and contribute to better people's lives, without ever compromising on the quality of the science. He has been a constant source of inspiration for me, in particular when it comes to communicating research results with excitement.

My second stay at INRAE was under the direction of Eric Justes. I've learnt a lot about crop modelling with Eric, and this knowledge now serves me almost on a daily basis – thanks so much Eric. Etienne Pascal-Journet and Laurent Bedoussac also contributed to make this stay at INRAE a great experience. Thank EPJ and Laurent for your guidance back at that time, and the very nice informal moments shared together.

Then I joined Cirad. Eric Justes was instrumental in motivating me to make the move. So was François Affholder. I am immensely grateful to François, who has been completing (it's not over yet) my training on crop modelling initiated by Eric. François also contributed to open my mind on the issues faced by smallholder farmers, and how it is key to understand (and try to influence!) the broader policy setting. Marc Corbeels urged me to join Cirad – and he was right - I've enjoyed it a lot so far. Thanks a lot Marc for your constant scientific support and guidance. I am also indebted to Edward Gerardeaux, Eric Scopel, Krishna Naudin, Julien Demenois and Jean Paul Laclau, who have always supported me over these years at Cirad – allowing me to thrive in this environment.

In Zimbabwe, I spend a fair deal of my time either at the University of Zimbabwe (UZ), or Cimmyt. At UZ, I want to thank Regis Chikowo, who has always helped to make the collaboration fruitful 'Masvita zvikuru Prof'. I am grateful to Bruno Gerard who facilitated my secondment to Cimmyt, and also to Vimbayi Chimonyo, who made it possible over the past years. Also, thanks to the field assistants who facilitate the connection with farmers and local stakeholders: Loveness Mudarikwa, Tinotenda Chirimamhunga, Zvisinei Matambo, Nyasha Muzhingi.

I would also like to thank Frederic Baudron. Fred, I would not have been able to write this dissertation without the motivation you gave me – thanks so much for going through the whole document and

providing directions for improvement. I really enjoyed reading your HDR dissertation, which was a great source of inspiration for me when I had to write mine.

I am grateful to several colleagues for daily interactions and coffee breaks, joint student supervision, joint work on scientific papers – all of which was instrumental in developing the ideas that are included in this dissertation: Frederic Baudron, Antoine Couëdel, Rémi Cardinael, Guillaume Bruelle, Louise Leroux, Aude Ripoche, Lalaina Ranaivoson, Juliette Lairez, David Berre, Michel Giner, Cyrille Midingoyi, Benjamin Heuclin, Mathias Christina, Romain Loison, Sandrine Auzoux, Julie Dusserre, Louis-Marie Raboin, Michel Vaksman, Myriam Adam, Camille Jahel, Nadine Andrieu, Marc Piraux, Camila Rebolledo, Damien Jourdain, Benjamin Sultan, Joao Silva, Chloe MacLaren.

Heartfelt thanks to the students I have had the chance to co-supervise – for some of them the journey is still on-going: Amadou Traore, Yolande Senghor, Rumbidzai Nyawasha, Valentin Prêt, Juliet Murimwa, Hardlife Chinwa, Adrien Coquereau, Mathilde de Freitas, Jakob Hambuchen, Marie Ruillé, Laurène Brun-Berger, Jean Alain Civil, Argeo Ulrich, Emma Sinibaldi, Illiana Kwenda, Oscar Chigodora.

Special thanks to Mathieu Bourgarel and Pierre Grard for having facilitated my institutional integration while in Zimbabwe, and to colleagues at Cirad/IRD/BioHub-Zimbabwe who have made the recent years a real pleasure at work: George Mapuvire, Grey Mashoko, Héléne De Nys, Valérie Pinarello, Vladimir Grosbois, Anne Conan, Eve Miguel, Florian Liegeois.

I extend my thanks to project managers who have always helped me make things happen, and compensate for my poor organizational skills: Leticia Dzido, Sabrina Azouni, Rahel Assefa, Rose Faju, Yvonne Maumbe, Letween Mutasa, Komborero Madzvova, Godfree Muduve.

I am grateful to my parents, they have always made it easy for me to carry-on with my studies. Lastly, I want thank my partner Emeline and our three beautiful children - your daily joy and enthusiasm bring me so much energy!

TABLE OF CONTENT

PART A – PRESENTATION OF THE CANDIDATE	11
I. Curriculum vitae	12
II. Biography (commented).....	13
1. Childhood and training (1986 – 2010).....	13
2. Farming system design in West Africa (2011-2015).....	13
3. Back in France – modelling agroecological sustainable intensification options (2015-2021) 14	
4. Southern Africa (2022 – present)	15
III. Publications:	16
1. Peer-reviewed published articles (supervised PhD students in bold).....	17
2. Peer-reviewed papers under review or in preparation.....	19
3. Peer-reviewed book chapters	21
4. Books	22
IV. Participation to international congresses as speaker	22
V. Supervision of students work	23
1. PhD students	23
2. Msc students	24
3. Past and current research projects	24
4. Collaborations	26
PART B: SYNTHESIS OF MY RESEARCH ACTIVITIES	27
I. Context	28
II. Overall research framework.....	28
III. Main results.....	30
1. Theme 1: Understanding the processes explaining the observed benefits of sustainable intensification options.....	30
2. Theme 2: Understanding the inter-annual variability in the performance of sustainable intensification options and opportunities to mitigate climate risk.....	32
3. Theme 3: Incorporating farm-level constraints and opportunities in the analysis of systems' transition towards sustainable intensification.....	36
4. Theme 4: Assessing scaling opportunities for place-based research results at regional/country level	40
PART C: PROJECT PROPOSAL	43
I. Introduction.....	43

1.	Challenges and opportunities to scale plot-level findings	43
2.	Challenges and opportunities to scale farm-level findings	44
3.	Incorporating landscape considerations	45
II.	A research framework for a multi-level assessment.....	46
1.	Study/calibration sites.....	49
2.	Analytical tools	49
3.	Typical outputs	49
4.	Interactions between field, farm, and landscape outcomes.....	50
III.	Expected results	50
1.	How does spatial and temporal variation in climate and soils drives the agronomic and environmental performance of sustainable intensification options?	50
2.	What are key trade-offs for resource allocation at farm level (cash, labour, land), and how does this vary locally (farm type) and more broadly across the continent (agroecological zones)? 53	
3.	Which landscape composition and configuration help reconcile food security, climate change mitigation and biodiversity conservation?	54
	REFERENCES	58
	SUMMARY (IN FRENCH)	62
	REPRINTS OF SELECTED PUBLICATIONS	72

LIST OF TABLES

<i>Table 1: Number of published articles per journal with impact factor. Most frequent journals in bold.</i>	
.....	16
<i>Table 2: List of past and current research projects</i>	25
<i>Table 3: Principal collaborations (at least two research papers published with these institutes)</i>	26
<i>Table 4: Projects and students to support the research project. Supervised students are underlined.</i>	56

LIST OF FIGURES

Figure 1: Research themes according to the temporal and spatial scale of analysis.....	29
Figure 2: A) Cowpea and sorghum partial Land Equivalent Ratio (intercrop productivity over sole crop productivity, pLER) as observed in the on-station experiment in southern Mali [PA16] (Blue dots are F1, 38 kgN/ha, and red dots are F0, 0 kgN/ha), B) Millet and cowpea pLER as observed in the on-station experiment in central Senegal [PA20] (the horizontal and vertical dotted lines indicate millet and cowpea relative densities in the mixture compared to sole cropping), C) Maize and cowpea pLER as observed in the on-farm trials in southern Mali [PA3], D) Cumulative probability distribution of the benefit/cost ratio of combined mineral and organic fertilizer application (DAP 75 kg/ha and compost 9t/ha) on a local sorghum variety in southern Mali (the dashed lines indicate the probability of achieving a benefit/cost ratio equal to one; Data from 20 to 26 on-farm trials in southern Mali in 2013 and 2014, respectively, the figure was adapted from [PA4]). In A, B and C the black solid line indicates a LER of 1.	31
Figure 3: (A) Observed (crosses with standard deviation if known) and simulated (box plots) grain yields at five representative experimental sites in sub-Saharan Africa. Simulations are from an ensemble of 25 partially and fully calibrated models. Black open dots are outliers. (B) relative Root Mean Square Error (rRMSE, averaged across all models) of simulated – observed comparison for six variables of interest. For aboveground plant nitrogen the comparison was possible for four of the ten experiments only (Benin and Ghana). Open dots indicate rRMSE of ensemble median. (C) Coefficient of variation (averaged across sites) of 25 model simulations for five variables.	33
Figure 4: A) Observed N_2 fixed at harvest by fababean (on-station experiments in southern France) and simulated water deficit factor for N_2 fixation during grain filling [PA8], B) Observed and simulated plant N uptake at flowering according to residue type and level of fertilization in Madagascar [PA17], and C) Observed and simulated grain yield in a sorghum/cowpea intercropping experiment in southern Mali [PA16] (green dots are sole sorghum, blue dots are intercropped sorghum, the black dot is sole cowpea, and red dots are intercropped cowpea).	34
Figure 5: A) Gains in rice Nitrogen Agronomic Efficiency (NAE) due to green manure incorporation compared to rice residue incorporation, as a function of N leaching for 25 simulated rice growing season in Madagascar highlands [PA17], B) Median and Inter Quartile Range (IQR) of productivity (for energy) of eight sustainable intensification options in southern Mali [PA23], C) Relations between pLER of aboveground biomass (AGB, log transformed value) for maize against simulated water stress averaged during reproductive phases in semi-arid Zimbabwe [RA5].	35
Figure 6: Simulation of 27 seasons of water and nitrogen-limited yield for groundnut and maize fertilized with 80 kgN/ha (plain line) in sub-humid Zimbabwe [RA9]. Dashed line is the maximum water and nitrogen-limited yield over the 27 seasons (Y_{max}). The grey shaded area indicates yield above 70% of Y_{max}	36
Figure 7: A) Conceptual representation of four farm types in a three-dimensional space of resource endowment, land productivity and combined labour productivity and food self-sufficiency, based on a panel survey that monitored 30 farms in the Koutiala district in southern Mali from 1994 to 2010 [PA2], B) Household (hh) food availability ratio (FA) for 2435 households in Tanzania [PA21]. The y-axis was log-transformed so that $y = \log(FA + 1)$. Households were ordered by increasing food availability ratio (i.e., the ratio of available food to the required food) along the x-axis. A bar is one household. The red dashed line is the 5000 kcal/capita/day food security threshold (i.e., food availability ratio = 2), and the blue dashed line is the 2500 kcal/capita/per day food security threshold (i.e., food availability ratio = 1). A rolling average was applied with subsets of 30 households to smooth the curves for easier interpretation. Different colours indicate the source of the food, be it	

<i>produced on-farm or purchased. Crops were considered as cash crops when >90% of the annual production was sold. Large values of sold and consumed crop on the right side of the plots correspond to potential bias in survey data rather than to real consumption values.</i>	<i>37</i>
<i>Figure 8: Effects of replacing sorghum on selected farm performance indicators, resulting from the ex-ante trade-off analysis for Medium Resource Endowed (MRE) farms (n =2) and Low Resource Endowed (LRE) farms (n =4) in southern Mali. For MRE farms, sorghum is replaced by soybean on black soils after cotton and maize, for LRE farms sorghum is replaced by cowpea grain variety on gravelly or sandy soils. Vertical bars represent twice the standard error of the mean. The horizontal dashed line in the “Food self-sufficiency” plots represents the food self-sufficiency threshold of one, meaning all household energy needs are provided by the household’s own cereal production.</i>	<i>38</i>
<i>Figure 9: Boxplots of relative change in Food availability ratio (FA) with the use of profit-maximizing mineral fertilizer, disaggregated per FA class in Tanzania and Uganda. The boxplots show the variability of the impact of Food availability across the surveyed households (2435 households in Tanzania and 1753 households in Uganda).</i>	<i>39</i>
<i>Figure 10: Food self-sufficiency ratio and income per capita of the 99 households of Nampossela village in southern Mali in 2013 (a) and 2027 for different scenarios of agricultural intensification and policy intervention (b, c, d, e, f) for an average rainfall year (734 mm). The horizontal and vertical dotted lines represent the 1.25 \$PPP/day poverty line and the food self-sufficiency threshold, respectively.</i>	<i>40</i>
<i>Figure 11: A) Maximum relative increase in yield (i.e., yield with maximum (200 N/20P/20 K) fertilizer application divided by control yield) as predicted by the random forest model (areas in Uganda and Tanzania where maize is not grown, according to IFPRI, 2020, appear in white). B) map of regional median relative change in food availability ratio for food insecure maize-growers, and C) map of relative increase in regional maize supply. One pitfall of the machine learning model was its low sensitivity to inter-annual variations in rainfall, precluding the analysis of the risk associated with the use of mineral fertiliser (i.e., low response in some dry years). Dynamic soil crop models can be useful to analyze and simulate this variation in inter-annual response to fertiliser. In that direction, we have been developing a platform for multi-model simulation and spatial exploration [PA25].</i>	<i>41</i>
<i>Figure 12: A) Millet yield gap (%difference to the 95th percentile) over the study area at patch scale using remote sensing information, B) marginal effect (partial dependence plot) of woody cover in surrounding landscape of millet patches on predicted yield gap.</i>	<i>42</i>
<i>Figure 13: Framework for the multi-level (field-farm-landscape) analysis of the impact of sustainable intensification options on food security, climate change adaptation and mitigation, and biodiversity conservation. Black dots are study sites for data collection and model refinement. Coloured rounds, stars and triangles are possible contrasting farm types at the study sites.</i>	<i>47</i>
<i>Figure 14: Typical outputs of the analytical framework at field (A), farm (B) and landscape (C) levels. Figure 2A is extracted from [RA4], Figure 2B is adapted from the Master thesis of L. Brun Berger (see part A) and Figure C is adapted from [RA14]. SI: Sustainable Intensification.</i>	<i>48</i>

LIST OF ABBREVIATIONS

AGAP:	Genetic Improvement and Adaptation of Mediterranean and Tropical Plants
AGIR:	AGroecologies, Innovations & Ruralities
AGMIP:	Agricultural model improvement and intercomparison
AIDA:	Agroecology and sustainable intensification of annual crops
ARISE:	Agriculture, resilience, inclusive and sustainable enterprise
CGIAR:	Consultative Group on International Agricultural Research
CIMMYT:	International Maize and Wheat Improvement Center
CIRAD:	French Agricultural Research Centre for International Development
ENSAT:	École Nationale Supérieure Agronomique de Toulouse
GDP:	Growth Domestic Product
ICRISAT:	International Crops Research Institute for the Semi-Arid Tropics
ILRI:	International Livestock Research Institute
IPCC:	Intergovernmental Panel on Climate Change
INRA:	French National Research Institute for Agriculture, Food and Environment
INTPA:	Directorate-General for International Partnerships
IRC:	Institut des Régions Chaudes
IRD:	French National Research Institute for Sustainable Development
LIPS-Zim:	Adoption and scaling up of improved livestock production systems in Zimbabwe
LSMS-ISA:	Living Standard Measurement Study – Integrated Surveys on Agriculture
PEPR:	Priority Research Programmes and Equipments
PERSYST:	Performance of Tropical Production and Processing Systems
RAIZ:	Promoting agroecological intensification for resilience building
RHOMIS:	The Rural Household Multi-Indicator Survey
UC-DAVIS:	The University of California, Davis
UMR:	Joint Research Unit
UPR:	Research Unit
STICS:	Simulateur multi-disciplinaire pour les Cultures Standard
WUR:	Wageningen University & Research

PART A – PRESENTATION OF THE CANDIDATE



I. Curriculum vitae

Gatien FALCONNIER

Nationality:	French			
Date of birth:	18/01/1986			
Marital status:	Cohabitation, 3 children			
Professional address:	Cirad Persyst University of Zimbabwe - Dept. of Crop Sciences - Mount Pleasant - PO Box MP 167 Harare Zimbabwe Email : gatien.falconnier@cirad.fr			
Profession:	Systems Agronomist			
Current position:	Researcher Centre de coopération internationale en recherche agronomique pour le développement Performances des systèmes de production et de transformation tropicaux			
Unit:	UPR Agro-écologie et intensification durable des cultures annuelles			
Expertise:	Scientific Systems Agronomy			
Expertise in country:	Mali, Sénégal, Zimbabwe			
Main qualifications:	Crop/farm modelling, On-station and on-farm experimentation, Agronomy, Participatory research, Crop-livestock integration			
Languages:	Level 1 (basic) to 5 (excellent)	Reading	Oral	Written
	French	5	5	5
	English	5	4	4
	Bambara	3	3	1
	Shona	2	2	1
Education:	2016 PhD – PE&RC graduate school - WUR 2011 Diplôme d'Ingénieur - Institut des Régions chaudes - Agronomie des Régions chaudes, agronomie et innovations en milieu rural 2005 (Niveau Bac + 2 (autre)) Lycée La Martinière, Monplaisir, Lyon, Cycle préparatoire BCPST (Biol. Chimie, Physique SVT) 2003 Bac S (Baccalauréat)			
Continuing education:	The International Summer School : Modelling Food Security – From 08/09/2019 to 14/09/2019 Assessing Crop Production with Simulation Models – From 14/05/2018 to 19/05/2018 EC-Analyse de sensibilité, métamodélisation et optimisation modèles complexes – From 26/03/2018 to 30/03/2018			

Professional experience:	01/2011 - 11/2011: Engineer at INRAE – UMR Innovation. Impact of ducks on weed infestation of rice field in Camargue
	11/2011 - 12/2014 : Associate Professional Officer (APO) at ICRISAT/Samanko – Mali Crop-livestock integration in southern Mali
	07/2016 - 12/2017: Post-doc at INRA Toulouse- UMR Agir Legume integration in cropping systems in southern France
	01/2018 – to date: Researcher at Cirad - AIDA

II. Biography (commented)

1. Childhood and training (1986 – 2010)

I was born in 1986 in a small city at the foot of the French Alps. My first experience with Africa was at the age of six, when my family moved to Côte d'Ivoire where I attended French primary and secondary school. Back in France in 1998 I completed my secondary education in the high school of Villefranche sur Saône. After two years of national preparatory program in Lyon, my career as a systems agronomist began with agronomy studies at ENSAT in Toulouse. During my ENSAT training, I had the opportunity to spend a year in Mali with CIRAD, as an intern, exploring the agroecological intensification of cotton production systems. I contributed to the writing of a scientific publication based on my fieldwork and analysis [PA1]. I completed my training studying Tropical Agronomy at IRC Supagro (2009-2010) and did two internships at ICRISAT Mali, conducting household survey in rural settings. During these two additional stays in Mali I was able to learn the local language, Bambara. I joined INRA in 2011, as a research engineer studying the impact of crop management on weeds in the rice plots in the French Camargue. The data I collected and my analysis formed the basis of a book chapter [BC1].

2. Farming system design in West Africa (2011-2015)

I then applied to, and obtained a junior expert position at the International Crop Research Institute for Semi-Arid Tropics (ICRISAT) in Bamako, Mali, with a specific focus on the understanding of crop-livestock interactions. At the same time, I embarked on a PhD Program at Wageningen University (WUR) under the supervision of Professor Ken Giller. My PhD work dealt with the design of innovative production systems in southern Mali, combining on-farm experimentation, ex-ante analysis and participatory work. I was able to i) participate in the drafting of projects that supported my fieldwork, ii) establish and monitor a large experimental set-up in farmers' fields iii) supervise students and field technicians involved in data collection, iv) partner with local researchers of the Institut d'Economie Rurale (IER Mali), v) defend my thesis [BK1] made of four published chapters [PA2][PA3][PA6][PA7], and vi) build a strong network of international scientific partners within CIRAD, the CGIAR centers and WUR. During my thesis I also contributed to two published papers [PA4][PA5]. My previous stays in Mali, and my ability to speak Bambara, greatly facilitated the participatory work that I carried-out during my PhD research.

3. Back in France – modelling agroecological sustainable intensification options (2015-2021)

After my PhD thesis, I was a post-doctoral fellow at UMR AGIR of INRAE, studying the contribution of legumes to the agroecological transition; I was able to develop my skills in crop modeling and publish two papers [PA8][PA9]. In early 2018, I was eager to come back to the study of agricultural issues related to the tropical world. I joined CIRAD's AIDA unit (Agroecology and Sustainable Intensification of Annual Crops) as a “Modeling Agronomist for Adaptation and Impacts of Climate Change on Food Security in sub-Saharan Africa”.

I stayed four years in Montpellier-CIRAD (2018-2021). My primary objective was to produce new scientific knowledge on the performance of crop models under tropical conditions, to explore the potential of sustainable intensification. For this, I built on the partnership within the ‘Agricultural model improvement and intercomparison’ (AGMIP) project, developed earlier by colleagues (M. Corbeels and F. Affholder, AIDA research unit, and M. Adam, AGAP research unit). AGMIP is an international effort that links communities of climate, crop, livestock, nutrition and economic modelers to analyze the impact of climate change on the agricultural sector. I coordinated over two years a modelling effort involving 25 modelling groups across the world, dedicated to low-input cropping systems in sub-Saharan Africa. This led to the publication of one main article [PA12] that established the foundations of the scientific agenda for AGMIP activities around low-input agriculture in Africa. I was also involved in the ‘agriculture, resilience, inclusive and sustainable enterprise’ (ARISE) project. I contributed to develop a modelling framework that facilitates the use of several crop models [PA25]. I also began to develop new skills for the unit, building with the University of Utrecht (Netherlands), a soft coupling between crop models and a hydrological model, with the ambition of comparing investments in irrigation and insurance as tools for reducing climate risks [PA31].

My secondary objective while in Montpellier was to study the effects of sustainable intensification and climate change on food security at regional level. For this I built on CIRAD's “Global Agronomy” initiative. With the support of the PERSYST department at Cirad and colleagues at AIDA, I initiated a workshop in 2019 on the importance of mineral fertilizers for food security in sub-Saharan Africa, that brought together 20 participants from several international institutions (CIMMYT, ILRI, WUR, UC DAVIS, IRD, INRAE) and CIRAD (AIDA and HORTSYS research units). The workshop helped outlining a research paper. The article, now published [PA21], stresses the important and necessary contribution of mineral fertilizers to reducing food insecurity in sub-Saharan Africa.

During my stay in Montpellier I also developed collaboration with CIRAD colleagues inside and outside my research unit, helping carry-out analyses with my expertise on cropping and farming systems analysis, that led to five publications [PA11][PA13][PA14][PA17][PA19]. This period in Montpellier was also a period of active involvement in the supervision of PhD and master students. Thanks to a senior colleagues at AIDA, Francois Affholder, I was closely involved in the supervision of i) a Phd research at ‘Sorbonne Université’ conducted by Amadou Traore that led to three published papers [PA15][PA16][PA23] and ii) a PhD research at ‘Université Gaston Berger’ in Senegal, conducted by Yolande Senghor, that led to one published paper [PA20]. I also provided specific support for individual papers for four other PhD students [PA10][PA18][PA26][PA28]. I supervised three Master 2 students who defended their thesis for IRC Supagro, AgroParisTech and WUR. I was also invited to participate in the thesis committees of Aminata Ganème (Joseph Ki Zerbo University, Burkina Faso), Edouard Sorry (ABIES graduate school, France), Joao Nuvunga (GAIA graduate school, France) and Mounir Senghouani (University of Bordeaux, France).

4. Southern Africa (2022 – present)

In 2021, I participated in the drafting of the Desira project “Promoting agroecological intensification for resilience building” (RAIZ) in response to the European Commission's Desira call. This new project supported my expatriation to Zimbabwe. I also developed a PhD proposal at WUR and now supervise the PhD candidate Valentin Pret. The work of Valentin has currently led to the publication of one paper [PA29], and three other papers are in preparation [RA8][RA9][RA10]. Valentin will submit his thesis by the end of the year. I also contributed, together with a colleague at Cirad-Tetis, to the development of another PhD proposal on the dynamics of land use change, at the landscape scale (Adrien Coquereau, Ecole Doctorale ABIES, France). Adrien is currently preparing one paper [RA14].

In Zimbabwe, I am seconded to the university of Zimbabwe and I am currently supervising two PhD students from the university: Rumbidzai Nyawasha and Juliet Murimwa. The work of Rumbidzai has led to one publication [PA27] and one paper is in preparation [RA6]. Juliet is currently preparing her first research paper [RA15]. I am also supervising two Master's students from the University of Zimbabwe, Illiana Kwenda (LIPS-Zim project) and Oscar Chigodora (RAIZ project). The work of Illiana has led to one paper ready to be submitted [RA5]. Within RAIZ, I have been coordinating the work package on the evaluation of the systems tested by the project at plot, farm and landscape scales. This gives me the opportunity to coordinate the activities of PhD students from CIRAD and the University of Zimbabwe. I also coordinate the implementation of field trials for the RAIZ project, providing a link between PhD students, UZ technicians and extension agents.

Since January 2022, I've been seconded to CIMMYT on a part-time basis. This is also an opportunity for me to strengthen links between CIRAD and CIMMYT, notably through my participation as coordinator of Zimbabwe activities for one work package of the OneCG initiative “Transformational Agroecology across food, land and water systems”. I contributed to a research paper that has recently been submitted on a survey tool for the evaluation of Agroecology [RA1].

I also continue to lead, together with AIDA colleagues, the Agmip/low input group. Jointly with a younger colleague at AIDA research unit, Antoine Couëdel, we coordinate two new exercises, one on the simulation of long-term carbon dynamics, and the other of the impact of past climate change on maize production in Africa. This has already led to one published paper [PA24], one paper under review [RA3] and two other papers are in preparation [RA12][RA13]. I was able to maintain connections with WUR through the supervision of a postdoc who published one paper on participatory modelling [PA30], and build stronger connections with colleagues of the AGAP research unit through the supervision of another post-doc [RA11].

Recently, the journal ‘Outlook on Agriculture’ invited my former PhD promotor K. Giller to write a perspective paper on agroecology in Africa and the role that mineral fertilizer should play. K. Giller offered me the opportunity to lead that paper. We wrote the paper together with colleagues at Cirad-Aida and African colleagues. The paper claims that ‘the input reduction principle is wrong when it comes to mineral fertilizer in sub-Saharan Africa’. The paper was published last year [PA22] and I was invited to present the results and our opinion in two international conferences [IC10][IC11].

III. Publications:

Table 1 lists the journals in which I have published, sorted by decreasing impact factor. More than half of the papers I published were in Agronomy for Sustainable Development, Agricultural Systems, Field Crops Research and European Journal of Agronomy.

Table 1: Number of published articles per journal with impact factor. Most frequent journals in bold.

Journal	Journal Impact factor	Number of published articles
Global Change Biology	10.8	1
Agronomy for Sustainable Development	6.4	3
Agricultural Systems	6.1	5
Land Use Policy	6	1
Field Crops Research	5.6	7
Environmental Development	4.7	1
Journal of Hydrology: Regional Studies	4.7	1
European Journal of Agronomy	4.5	3
European Journal of Soil Science	4	1
Outlook on Agriculture	3.5	1
Heliyon	3.4	1
Regional Environmental Change	3.4	1
Geoderma Regional	3.1	1
SoftwareX	2.4	1
Weather, Climate, and Society	1.9	1
Experimental Agriculture	1.6	1
Cahiers Agricultures	1	1
		Total = 31

1. Peer-reviewed published articles (supervised PhD students in bold)

- [PA1] Autfray, P., Sissoko, F., Falconnier, G.N., Ba, A., Dugué, P., 2012. Usages des résidus de récolte et gestion intégrée de la fertilité des sols dans les systèmes de polyculture élevage : étude de cas au Mali-Sud. *Cahiers Agricultures* 21, 225–234.
- [PA2] Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways: Two decades of change in southern Mali. *Agricultural Systems* 139, 210–222
- [PA3] Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of sustainable intensification options in southern Mali. *Field Crops Research* 187, 113–126.
- [PA4] Descheemaeker, K., Ronner, E., Ollenburger, M., Franke, A.C., Klapwijk, C.J., Falconnier, G.N., Wichern, J., Giller, K.E., 2016b. Which options fit best? Operationalizing the socio-ecological niche concept. *Experimental Agriculture* 1–22.
- [PA5] Descheemaeker, K., Oosting, S.J., Tui, S.H.-K., Masikati, P., Falconnier, G.N., Giller, K.E., 2016a. Climate change adaptation and mitigation in smallholder crop–livestock systems in sub-Saharan Africa: a call for integrated impact assessments. *Reg Environ Change* 16, 2331–2343.
- [PA6] Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K.E., 2017. Co-learning cycles to support the design of innovative farm systems in southern Mali. *European Journal of Agronomy* 89, 61–74.
- [PA7] Falconnier, G.N., Descheemaeker, K., Traore, B., Bayoko, A., Giller, K.E., 2018. Agricultural intensification and policy interventions: Exploring plausible futures for smallholder farmers in Southern Mali. *Land Use Policy* 70, 623–634.
- [PA8] Falconnier, G.N., Journet, E.-P., Bedoussac, L., Vermue, A., Chlébowski, F., Beaudoin, N., Justes, E., 2019. Calibration and evaluation of the STICS soil-crop model for faba bean to explain variability in yield and N₂ fixation. *European Journal of Agronomy* 104, 63–77.
- [PA9] Falconnier, G.N., Vermue, A., Journet, E.-P., Christina, M., Bedoussac, L., Justes, E., 2020b. Contrasted response to climate change of winter and spring grain legumes in southwestern France. *Field Crops Research* 259, 107967.
- [PA10] Lairez, J., Lopez-Ridaura, S., Jourdain, D., Falconnier, G.N., Lienhard, P., Striffler, B., Syfongxay, C., Affholder, F., 2020. Context matters: Agronomic field monitoring and participatory research to identify criteria of farming system sustainability in South-East Asia. *Agricultural Systems* 182, 102830.
- [PA11] Leroux, L., Falconnier, G.N., Diouf, A.A., Ndao, B., Gbodjo, J.E., Tall, L., Balde, A.A., Clermont-Dauphin, C., Bégué, A., Affholder, F., Rounsard, O., 2020. Using remote sensing to assess the effect of trees on millet yield in complex parklands of Central Senegal. *Agricultural Systems* 184, 102918.
- [PA12] Falconnier, G.N., Corbeels, M., Boote, K.J., Affholder, F., Adam, M., MacCarthy, D.S., Ruane, A.C., Nendel, C., Whitbread, A.M., Justes, É., Ahuja, L.R., Akinseye, F.M., Alou, I.N., Amouzou, K.A., Anapalli, S.S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., Challinor, A.J., Chen, Y., Deryng, D., Elsayed, M.L., Faye, B., Gaiser, T., Galdos, M., Gayler, S., Gerardeaux, E., Giner, M., Grant, B., Hoogenboom, G., Ibrahim, E.S., Kamali, B., Kersebaum, K.C., Kim, S.-H., Laan, M. van der, Leroux, L., Lizaso, J.I., Maestrini, B., Meier, E.A., Mequanint, F., Ndoli, A., Porter, C.H.,

- Priesack, E., Ripoche, D., Sida, T.S., Singh, U., Smith, W.N., Srivastava, A., Sinha, S., Tao, F., Thorburn, P.J., Timlin, D., Traore, B., Twine, T., Webber, H., 2020a. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. *Global Change Biology* 26, 5942–5964.
- [PA13] Gérardeaux, E., Falconnier, G., Gozé, E., Defrance, D., Kouakou, P.-M., Loison, R., Sultan, B., Affholder, F., Muller, B., 2021. Adapting rainfed rice to climate change: a case study in Senegal. *Agronomy for Sustainable Development* 41, 57.
- [PA14] Leroux, L., Faye, N.F., Jahel, C., Falconnier, G.N., Diouf, A.A., Ndao, B., Tiaw, I., Senghor, Y., Kanfany, G., Balde, A., Dieye, M., Sirdey, N., Aloba Loison, S., Corbeels, M., Baudron, F., Bouquet, E., 2022. Exploring the agricultural landscape diversity-food security nexus: an analysis in two contrasted parklands of Central Senegal. *Agricultural Systems* 196, 103312.
- [PA15] **Traoré, A.**, Falconnier, G.N., Kouressi, M., Serpentié, G., BA, A., Affholder, F., Giner, M., Sultan, B., 2022. Farmers' Perception and Adaptation Strategies to Climate Change in Central Mali. *Weather, Climate, and Society* 14, 95–112.
- [PA16] **Traoré, A.**, Falconnier, G.N., Ba, A., Sissoko, F., Sultan, B., Affholder, F., 2022. Modeling sorghum-cowpea intercropping for a site in the savannah zone of Mali: Strengths and weaknesses of the Stics model. *Field Crops Research* 285, 108581.
- [PA17] Ranaivoson, L., Falconnier, G.N., Affholder, F., Leroux, L., Autfray, P., Muller, B., Auzoux, S., Ripoche, A., 2022. Can green manure contribute to sustainable intensification of rainfed rice production in Madagascar? *Field Crops Research* 289, 108711.
- [PA18] Nenkam, A.M., Wadoux, A.M.J.-C., Minasny, B., McBratney, A.B., Traore, P.C.S., Falconnier, G.N., Whitbread, A.M., 2022. Using homosoils for quantitative extrapolation of soil mapping models. *European Journal of Soil Science* 73, e13285.
- [PA19] Andrieu, N., Dumas, P., Hemmerlé, E., Caforio, F., Falconnier, G.N., Blanchard, M., Vayssières, J., 2021. Ex ante mapping of favorable zones for uptake of climate-smart agricultural practices: A case study in West Africa. *Environmental Development* 37, 100566.
- [PA20] **Senghor, Y.**, Balde, A.B., Manga, A.G.B., Affholder, F., Letourmy, P., Bassene, C., Kanfany, G., Ndiaye, M., Couedel, A., Leroux, L., Falconnier, G.N., 2023. Intercropping millet with low-density cowpea improves millet productivity for low and medium N input in semi-arid central Senegal. *Heliyon* 9, e17680.
- [PA21] Falconnier, G.N., Leroux, L., Beillouin, D., Corbeels, M., Hijmans, R.J., Bonilla-Cedrez, C., van Wijk, M., Descheemaeker, K., Zingore, S., Affholder, F., Lopez-Ridauro, S., Malézieux, E., Makowski, D., Rurinda, J., van Ittersum, M.K., Vanlauwe, B., Giller, K.E., Lammoglia, S.-K., Waha, K., 2023. Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa. *Agricultural Systems* 205, 103588.
- [PA22] Falconnier, G.N., Cardinael, R., Corbeels, M., Baudron, F., Chivenge, P., Couëdel, A., Ripoche, A., Affholder, F., Naudin, K., Benaillon, E., Rusinamhodzi, L., Leroux, L., Vanlauwe, B., Giller, K.E., 2023. The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in sub-Saharan Africa. *Outlook Agric* 00307270231199795.
- [PA23] **Traoré, A.**, Falconnier, G.N., Couëdel, A., Sultan, B., Chimonyo, V.G.P., Adam, M., Affholder, F., 2023. Sustainable intensification of sorghum-based cropping systems in semi-arid sub-Saharan Africa: The role of improved varieties, mineral fertilizer, and legume integration. *Field Crops Research* 304, 109180.

- [PA24] Couédel, A., Falconnier, G.N., Adam, M., Cardinael, R., Boote, K., Justes, E., Smith, W.N., Whitbread, A.M., Affholder, F., Balkovic, J., Basso, B., Bhatia, A., Chakrabarti, B., Chikowo, R., Christina, M., Faye, B., Ferchaud, F., Folberth, C., Akinseye, F.M., Gaiser, T., Galdos, M.V., Gayler, S., Gorooei, A., Grant, B., Guibert, H., Hoogenboom, G., Kamali, B., Laub, M., Maureira, F., Mequanint, F., Nendel, C., Porter, C.H., Ripoche, D., Ruane, A.C., Rusinamhodzi, L., Sharma, S., Singh, U., Six, J., Srivastava, A., Vanlauwe, B., Versini, A., Vianna, M., Webber, H., Weber, T.K.D., Zhang, C., Corbeels, M., 2024. Long-term soil organic carbon and crop yield feedbacks differ between 16 soil-crop models in sub-Saharan Africa. *European Journal of Agronomy* 155, 127109.
- [PA25] Giner, M., Affholder, F., Falconnier, G.N., Chimonyo, V.G.P., Leroux, L., Auzoux, S., Adam, M., Kouakou, P., Loison, R., Midingoyi, C.A., Chavez, E., 2024. ACME (Agile Crop Model Ensemble): A package to generate and run large virtual experiments with ensembles of crop simulation models. *SoftwareX* 27, 101777.
- [PA26] Gautron, R., Baudry, D., Adam, M., Falconnier, G.N., Hoogenboom, G., King, B., Corbeels, M., 2024. A new adaptive identification strategy of best crop management with farmers. *Field Crops Research* 307, 109249.
- [PA27] **Nyawasha, R.W.**, Wadoux, A.M.J.-C., Todoroff, P., Chikowo, R., Falconnier, G.N., Lagorsse, M., Corbeels, M., Cardinael, R., 2024. Multivariate regional deep learning prediction of soil properties from near-infrared, mid-infrared and their combined spectra. *Geoderma Regional* 37, e00805.
- [PA28] Sow, S., Senghor, Y., Sadio, K., Vezy, R., Rounsard, O., Affholder, F., N'dienor, M., Clermont-Dauphin, C., Gaglo, E.K., Ba, S., Tounkara, A., Balde, A.B., Agbohessou, Y., Seghieri, J., Sall, S.N., Couedel, A., Leroux, L., Jourdan, C., Diaite, D.S., Falconnier, G.N., 2024. Calibrating the STICS soil-crop model to explore the impact of agroforestry parklands on millet growth. *Field Crops Research* 306, 109206.
- [PA29] **Pret, V.**, Falconnier, G.N., Affholder, F., Corbeels, M., Chikowo, R., Descheemaeker, K., (Accepted for publication). Farm resilience to climatic risk – a review. *Agronomy for Sustainable Development*.
- [PA30] Cherié, T., Descheemaeker, K., Falconnier, G.N., Ganeme, A., Lairez, J., Sawadogo, H., Adam, M., (Accepted for publication). Mobilizing crop models in participatory research: A conceptual framework to facilitate communication with farmers. *Agronomy for Sustainable Development*.
- [PA31] Hoogeveen, A.C., Sutanudjaja, E.H., Falconnier, G.N., van Beek, L.P.H., Wanders, N., Bierkens, M.F.P., and Hoch, J.M. (Accepted for publication). Can small reservoirs and groundwater pumping increase water availability of small-holder farmers? A case study in the Senegal. *Journal of Hydrology: Regional Studies*.

2. Peer-reviewed papers under review or in preparation

Under review

- [RA1] Jones, S. K., Sánchez, B., Andrea C., Lamanna, C., Dickens, C., Geck, M. S., Wickramaratne, C., Alary, V., Bolo, P., Choruma, D.J., Douangsavan, S., Fall, M.G., Falconnier, G.N., Gupta, S., Kettle, C., Krishnan, S., Nyawira, S.S., Orjuela-Ramirez, G., Orounladji, B.M., Pareja, P., Sibanda, T., (Under review). Holistic Localized Performance Assessment (HOLPA) Tool for Collecting Locally Relevant and Globally Comparable Evidence of Agroecology's Effects on Nature and People. *OneEarth*.

- [RA2] Belard A., Jourdain D., Pedsiza T., Manyanga M., Gérard F., Falconnier G.N., Affholder F. (Under review) Understanding Smallholder Farmers' Preferences for Sustainable Agricultural Practices in Southern Africa: Insights from Rural Zimbabwe. *Agricultural Economics*.
- [RA3] Couëdel, A., Falconnier, G.N., Adam, M., Cardinael, R., Boote, K., Justes, E., Smith, W.N., Whitbread, A.M., Affholder, F., Balkovic, J., Basso, B., Bhatia, A., Chakrabarti, B., Chikowo, R., Christina, M., Faye, B., Ferchaud, F., Folberth, C., Akinseye, F.M., Gaiser, T., Galdos, M.V., Gayler, S., Gorooei, A., Grant, B., Guibert, H., Hoogenboom, G., Kamali, B., Laub, M., Maureira, F., Mequanint, F., Nendel, C., Porter, C.H., Ripoche, D., Ruane, A.C., Rusinamhodzi, L., Sharma, S., Singh, U., Six, J., Srivastava, A., Vanlauwe, B., Versini, A., Vianna, M., Webber, H., Weber, T.K.D., Zhang, C., Corbeels, M. (Under Review). Soil fertility loss outweighs climate change impact on maize yield in sub-Saharan Africa. *Nature Communications*

In preparation

- [RA4] Falconnier G.N., Midingoyi C., Corbeels, M., Leroux L., Chimonyo V., Couedel A., Gerardeaux E., Adam M, Loison R., Chavez E., Hoch, J., Affholder F. (In prep.). Identifying priority areas for de-risking sustainable intensification of crop production in sub-Saharan Africa: the case study of maize in central Senegal. *Agriculture, Forest and Meteorology*.
- [RA5] Kwenda I., Cardinael R., Magwaza E., Couedel A., de Freitas M., Diop S., Pret V., Baudron, F., Nyagumbo I., Frank L., Falconnier G.N. (In prep.). Water and nitrogen stress drive cereal-intercropping performance in on-farm trials in sub-humid Zimbabwe. *Field Crops Research*.
- [RA6] **Nyawasha R.**, Falconnier G.N., Todoroff P., Wadoux A.M.J.-C., Chikowo R., Coquereau A., Jahel C., Corbeels M., Cardinael R. (In prep.) Understanding drivers of soil organic carbon stocks in African mixed crop-livestock farming systems. *Geoderma Regional*.
- [RA7] **de Freitas M.**, Couëdel A., Falconnier G.N., Christina M., Balde A.B., Affholder F., Traore A., Ganeme A., Adam M., Senghor Y., Sow S., Justes E. (In prep.) Cereal-legume intercropping systems in tropical conditions: how does the STICS model reproduce complementarity and competition? *Field Crops Research*.
- [RA8] **Pret, V.**, Falconnier, G.N., Affholder, F., Corbeels, M., Chikowo, R., Cardinael R., Couedel A., Diop S., Kwenda I., Descheemaeker, K. (In Prep.) Modelling sustainable intensification options in smallholder fields in sub-humid Zimbabwe with the STICS model: achievements and challenges. *Field Crops Research*.
- [RA9] **Pret, V.**, Falconnier, G.N., Affholder, F., Corbeels, M., Chikowo, R., Descheemaeker, K., (In prep.) Groundnut is less sensitive to climate inter-annual variability than intensified maize in sub-humid Zimbabwe. *European Journal of Agronomy*.
- [RA10] **Pret, V.**, Falconnier, G.N., Affholder, F., Corbeels, M., Chikowo, R., Descheemaeker, K. (In prep.) Combining intensification and diversification with legumes improves agricultural and environmental performance of maize-based cropping systems in sub-humid Zimbabwe. *Agricultural Systems*.
- [RA11] Rebolledo M.C., Ranaivoson L., Falconnier G.N., Adam M., Ibrahim A., Mallikarjuna S, Kazuki S., McNally K. L. (In prep.) A Global Rice Field laboratory to understand rice response to climate variability. *Global Change Biology*.
- [RA12] Couëdel C., Laub M., Falconnier G.N., Ranaivomanana R., Falconnier G.N., Cardinael R., Six J., Corbeels M. (In prep) Similar performance of the DayCent and STICS models in simulating long-term yield and soil organic carbon dynamics in Kenya. *Field Crops Research*.

- [RA13] Brouillet A., Falconnier G.N., Iizumi T., Couedel A., Boote K.E., Hoogenboom G., Midingoyi C., Sotomayor M., Basso B., Akinseye F.M., Mequanint F., Diancoumba M., Kim Y., Gayler S., Kumar A., Webber H., Raza A., Smith W., Grant B., Affholder A., Sultan B. (In prep.) Impacts and attribution of human-induced excessive rainfall and drought on maize yields in low-inputs smallholder systems in Africa using crop models. *Nature Food*.
- [RA14] **Coquereau A.**, Falconnier G., Piraux M., Leroux L., Nyakahadzoi K., Jahel C. (In prep.) Contribution of agroecological landscapes to food security in sub-humid Zimbabwe. *Agricultural Systems*
- [RA15] **Murimwa J.**, Rugare J., Falconnier G.N., Chingwa H., Chikowo R., Mabasa S. (In prep.) Crop residue mulching and cereal-legume intercropping reduce weed pressure in smallholder fields of sub-humid and semi-arid Zimbabwe. *Field Crops Research*.

3. Peer-reviewed book chapters

- [BC1] Mouret Jean Claude, Falconnier Gatien N., 2018. La gestion des adventices en riziculture biologique. In : *Le riz et la Camargue : vers des agroécosystèmes durables*. Mouret Jean-Claude (ed.), Leclerc Bernadette (ed.). Dijon : Educagri-Cardère éd., 437-150. ISBN 979-10-275-0154-0 ; 978-2-37649-003-6
- [BC2] Adam Myriam, Boote Kenneth J., Falconnier Gatien N., Porter Cheryl, Eyshi Rezaei E., Webber Heidi. Modeling the effects of climate change on agriculture: a focus on cropping systems. 2020. In : *Climate change and agriculture*. Deryng Delphine (ed.). Cambridge: Burleigh Dodds Science Publishing, 55-95. (Burleigh Dodds Series in Agricultural Science)
- [BC3] Cardinael Rémi, Deheuvels Olivier, Leroux Louise, Subervie Julie, Suwa-Eisenmann Akiko, Bessou Cécile, Bouquet Emmanuelle, Catry Thibault, Chikowo Régis, Corbeels Marc, Demarchi Gabriela, Diouf Abdoul Aziz, Falconnier Gatien N., Faye Ndeye Fatou, Gignoux Jérémie, Icard-Vernière Christèle, Jahel Camille, Katic Pamela, Libois François, Mercier Sabine, Mouquet-Rivier Claire, Namatsheve Talent, Renk Andréa, Sirdey Ninon, Tritsch Isabelle, Verger Eric O.. 2022. Food security and natural resources: diversification strategies. In : *Sustainable food systems for food security. Need for combination of local and global approaches*. Thomas Alban (ed.), Alpha Arlène (ed.), Barczak Aleksandra (ed.), Zakhia-Rozis Nadine (ed.). Versailles : Ed. Quae, 171-185. (Synthèses : Quae) ISBN 978-2-7592-3575-9
- [BC4] Beaudoin Nicolas, Constantin Julie, Graux Anne-Isabelle, Falconnier Gatien, Affholder François, Ruget Françoise, Ruiz Laurent. 2023. Ways of STICS use. In : *STICS soil-crop model: conceptual framework, equations and uses*. Beaudoin Nicolas (ed.), Lecharpentier Patrice (ed.), Ripoche-Wachter Dominique (ed.), Strullu Loïc (ed.), Mary Bruno (ed.), Léonard Joël (ed.), Launay Marie (ed.), Justes Eric (ed.). Versailles: Ed. Quae, 281-321. (Update sciences et technologies) ISBN 978-2-7592-3678-7
- [BC5] Adam Myriam, Falconnier Gatien, Berre David, Descheemaeker Katrien, Lairez Juliette, Leroux Louise. 2023. Modeling climate change impact on low-input smallholder farming systems. In: *Modelling climate change impacts on agricultural systems*. Nendel Claas (ed.). Cambridge: Burleigh Dodds Science Publishing, 235-267. (Burleigh Dodds Series in Agricultural Science) ISBN 9781801461740 <https://doi.org/10.19103/AS.2022.0115.10>

4. Books

- [BK1] Falconnier Gatien N., 2016. Trajectories of agricultural change in southern Mali. Wageningen: Wageningen University, 219 p. ISBN 978-94-6257-759-6. Thesis Ph. D. : Wageningen University

IV. Participation to international congresses as speaker

- [IC1] Falconnier Gatien N., Sanogo Ousmane, Van Mourik T., Descheemaeker Katrien, Giller Ken E, 2013. Understanding farm trajectories for better targeting of agricultural technologies. In: Sustainable intensification of agriculture: Systems research helping to meet the needs and managing the trade-offs of a changing world. Chen Fu (ed.), Gao Wangsheng (ed.). s.l.: Gansu Science and Technology Press, 165-166. ISBN 7-5424-0961-1 International Symposium for Farming Systems Design. 4, Lanzhou, Chine, 19 Août 2013/22 Août 2013.
- [IC2] Falconnier Gatien N., Van Mourik Thomas A., Descheemaeker Katrien, 2014. Exploring intensification options for mixed crop-livestock farms in southern Mali. In: Book of abstracts of the ESA XIIIth Congress, 25-29 August 2014, Debrecen, Hungary. Pepo Péter (ed.), Csajbok Jozsef (ed). ESA. Debrecen: ESA, 325-326. ISBN 978-963-473-723-0 Congress of the European Society for Agronomy. 13, Debrecen, Hongrie, 25 Août 2014/29 Août 2014.
- [IC3] Falconnier Gatien N., Descheemaeker Katrien, Van Mourik Thomas A., Giller Ken E., 2015. Innovative participatory farming system design: combining on-farm crop/livestock trials with ex- ante trade-off analysis. In: FSD5 Proceedings: Multi-functional farming systems in a changing world. Gritti Emmanuel S. (ed.), Wery Jacques (ed.). Montpellier: European Society of Agronomy, 485-486. International Symposium Farming System Design. 5, Montpellier, France, 7 Septembre 2015/10 Septembre 2015.
- [IC4] Falconnier Gatien N., Vermue Anthony, Journet Etienne-Pascal, Bedoussac Laurent, Justes Eric, 2018. Assessment of the impact of climate change in temperate zone on grain legume yield and N₂ fixation. PS-4.1-05. In : Book of abstracts of the XV European Society for Agronomy Congress : "Innovative cropping . and farming systems for high quality food production systems". Agroscope. Genève : Agroscope, Résumé, 20. European Society for Agronomy Congress (ESA 2018). 15, Genève, Suisse, 27 Août 2018/31 Août 2018.http://www.esa-congress-2018.ch/wp-content/uploads/2018/08/ESA2018_AbstractBook_A4-1.pdf
<http://www.esa-congress-2018.ch/wp-content/uploads/2018/08/ESA2018_AbstractBook_A4-1.pdf>
- [IC5] Falconnier Gatien N., Corbeels Marc, Boote Ken, Adam Myriam, Basso Bruno, Ruane Alex C., AgMIP low input cropping systems team (collab.), 2019. Model intercomparison of maize response to climate change in low-input smallholder cropping systems. Budapest: Elsevier, 1 poster Agriculture and Climate Change Conference, Budapest, Hongrie, 24 Mars 2019/26 Mars 2019.
- [IC6] Falconnier Gatien N., Hambüchen Jakob, Adam Myriam, Huet Eva, Giller Ken E., Traore Bouba, Leroux Louise, Descheemaeker Katrien, 2019. Identifying changes in agricultural practices and policy interventions for sustainable intensification of farm systems in southern Mali. Farming Systems Design Community, Universidad de la República Uruguay. Montevideo: Farming Systems Design Community, 3 p. International Symposium for Farming Systems Design (FSD6). 6, Montevideo, Uruguay, 18 Août 2019/21 Août 2019.

- [IC7] Falconnier Gatien N., Corbeels Marc, Boote Kenneth J., Ruane Alex C., Whitbread Anthony M., Adam Myriam, Affholder François, Ahuja Lajpat R., Akinseye Folorunso M., Alou Isaac N., Amouzou Kokou A., Anapalli Saseendran S., Baron Christian, Basso Bruno, Baudron Frédéric, Bertuzzi Patrick, Challinor Andrew J., Chen Yi, Deryng Delphine, Elsayed Maha L., Faye Babacar, Gaiser Thomas, Galdos Marcelo, Gayler Sebastian, Gérardaux Edward, Giner Michel, Grant Brian, Hoogenboom Gerrit, Ibrahim Esther S., Justes Eric, Kamali Bahareh, Kersebaum Kurt Christian, Kim Soo-Hyung, Van Der Laan Michael, Leroux Louise, Lizaso Jon, MacCarthy Dilys Sefakor, Maestrini Bernardo, Meier Elizabeth A., Mequanint Fasil, Ndoli Alain, Nendel Claas, Porter Cheryl, Priesack Eckart, Ripoche Dominique, Sida Tesfaye S., Singh Upendra, Smith Ward N., Srivastava Amit Kumar, Sinha Sumit, Tao Fulu, Thorburn Peter J., Timlin Dennis, Traoré B., Twine Tracy E., Webber Heidi. 2020. Modeling of climate change impacts on maize yields in low-nitrogen conditions in Africa. CIRAD, INRAE, INRIA. Montpellier: CIRAD, 2 p. International Crop Modelling Symposium (iCROP 2020). 2, Montpellier, France, 3 Février 2020/5 Février 2020.
- [IC8] Falconnier, G.N., Leroux, L., Beillouin, D., Corbeels, M., Hijmans, R.J., Bonilla-Cedrez, C., van Wijk, M., Descheemaeker, K., Zingore, S., Affholder, F., Lopez-Ridaura, S., Malézieux, E., Makowski, D., Rurinda, J., van Ittersum, M.K., Vanlauwe, B., Giller, K.E., Lammoglia, S.-K., Waha, K., 2023. Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa. AgMIP. New York: AgMIP, Résumé, 2 p. AgMIP 9 Modeling the Future of Food, New York, États-Unis, 26 Juin 2023/30 Juin 2023.
- [IC9] Falconnier, G.N., **Traoré, A.**, Couëdel, A., Sultan, B., Chimonyo, V.G.P., Adam, M., Affholder, F., 2023. Sustainable intensification of sorghum-based cropping systems in semi-arid sub-Saharan Africa: The role of improved varieties, mineral fertilizer, and legume integration. AgMIP. New York: AgMIP, Résumé, 2 p. AgMIP 9 Modeling the Future of Food, New York, États-Unis, 26 Juin 2023/30 Juin 2023.
- [IC10] Falconnier, G.N., Cardinael, R., Corbeels, M., Baudron, F., Chivenge, P., Couëdel, A., Ripoche, A., Affholder, F., Naudin, K., Benaillon, E., Rusinamhodzi, L., Leroux, L., Vanlauwe, B., Giller, K.E., 2024. Use of mineral fertilizers in addition to agroecological practices to boost agricultural production in Africa. 60th Paris International Agricultural Show. Paris, France.
- [IC11] Falconnier, G.N., 2024. Using mineral fertilizers in agroecological approaches in Africa. SASI Initiative-FAO, EU and AgrinaturaSide event to the Africa Fertilizer and Soil Health Summit, Nairobi, Kenya

V. Supervision of students work

1. PhD students

A. Traore (2018-2022) Changement climatique et agriculture en Afrique subsaharienne : Perception des agriculteurs et impact de l'association entre une céréale et une légumineuse sur les rendements des deux espèces et leur variabilité inter-annuelle sous climat actuel et futur - Cas du sorgho et du niébé dans l'environnement soudano-sahélien. Sorbonne Université.

Y. Senghor (2019-2024) Association mil-niébé au Sénégal comme prototype de l'intensification écologique en milieu semi-aride : estimation des performances agronomique et de leur variabilité interannuelle en fonction du climat. Université Gaston Berger- Saint-Louis du Senegal.

R. Nyawasha (2020-2024) SOC sequestration across scales: a case study from a sub-humid region of Zimbabwe. University of Zimbabwe.

V. Prêt (2021-2024) Risk assessment of sustainable intensification farming systems in Zimbabwe, with a climate change adaptation and resilience building perspective. Wageningen University.

J. Murimwa (2022-to date) Ecologically based integrated weed management strategies for sustainable crop production across three agroecological regions in north-east Zimbabwe. University of Zimbabwe.

A. Coquereau (2023- to date) Agroecology at landscape scale: foresight for the transition of agricultural landscapes in the Murewha district of Zimbabwe. AgroParisTech

M. de Freitas (2023- to date) Évaluation de la résilience des cultures associées de céréales et de légumineuses face au changement et à la variabilité climatiques en Afrique sub-Saharienne. Institut Agro.

2. Msc students

J. Hambuchen (2019) Assessment of the potential future sustainability of smallholder farming in the 'old cotton basin' of Mali. Wageningen University.

M. Ruillé (2020) Can remote sensing data improve millet yield estimation in central Senegal? AgroParisTech.

L. Brun-Berger (2020) Assessing constraints and levers for soil carbon storage in smallholder farms of sub-humid Zimbabwe – Case study of Murehwa district. Institut Agro.

J. Civil (2022) Modélisation de la croissance et du rendement de l'arachide (*Arachis hypogaea* L.) en milieu tropical : cas du bassin arachidier du Sénégal. Institut Agro.

M. de Freitas (2023) Intercropping cereals and legumes to stabilise yield in the tropics: evaluation of the STICS soil-crop model to simulate bi-specific intercrops. AgroParisTech.

A. Ulrich (2023) The effect of sowing date sources on yield estimates of spatialized crop growth models in Sub-Saharan Africa. ETH Zürich.

E. Sinibaldi (2024) Can cereal-legume intercropping contribute to adaptation to climate variability and climate change across West Africa – a metamodeling approach. Université de Montpellier.

I. Kwenda (2024) Assessing the performance of maize and legume fodder crops under current and future climate: A case in Mutoko district, Zimbabwe. University of Zimbabwe.

O. Chigodora (2024) Selection of suitable sorghum (*Sorghum bicolor* L. Moench) genotypes for diverse farming systems in semi-arid and sub-humid Zimbabwe. University of Zimbabwe.

3. Past and current research projects

Table 2 below gives an overview of the projects I have been involved in, with details on supervision and leading activities.

Table 2: List of past and current research projects

Project	Funder	Country(ies)	Period	Role
Pathways to Agroecological intensification in southern Mali	McKnight fundation	Mali	2012-2015	Development of project proposal Supervision of technicians and experimentations
Africa Rising	USAID	Mali	2012-2015	Supervision of technicians and experimentations
CRP DrylandSystems	CGIAR	Mali	2012-2015	Supervision of technicians and experimentations
Legumes for the Agriculture of Tomorrow (LEGATO)	European Union	France	2016-2018	Data analysis
Agricultural Model Intercomparison and Improvement Project (AGMIP)	-	Global	2018-to date	Coordination of the 'low-input' smallholder activity
Dynamics of carbon sequestration in the soils of tropical and temperate farming systems (DSCATT)	Agropolis Fundation / Total Fundation	Senegal, Zimbabwe	2019-2023	Supervision of one PhD student
Agriculture Resilient, Inclusive, and Sustainable Enterprise (ARISE)	European Union (Eit Climate KIC)	Senegal, Zimbabwe	2020-2022	Model development and simulations analysis
Livestock Production Systems in Zimbabwe (LIPS-Zim)	European Union (Desira)	Zimbabwe	2021-2024	Supervision of one MPhil Student
Promoting agroecological intensification for resilience building (RAIZ)	European Union (Desira)	Zimbabwe	2021-2025	Development of project proposal Coordination of work package 'sustainability assessment' Supervision of three PhD students Supervision of one master student
IntercropValues	European Union (H2020)	Zimbabwe	2022-2025	Supervision of one PhD student
Transformational agroecology across food, land, and water systems - Agroecology Initiative	OneCGIAR	Zimbabwe	2023-2024	Coordinator of work package 'Holistic Assessment' for Zimbabwe

4. Collaborations

Table 3: Principal collaborations (at least two research papers published with these institutes)

Europe	France	CIRAD, INRAE, IRD, Université de Toulouse
	Netherlands	Wageningen University
	Germany	ZALF
North America	United States	University of Florida, NASA Goddard Institute for Space Studies
	Canada	Ottawa Research and Development Center (CAN)
Africa	Morocco	APNI
	Mali	ICRISAT, IER
	Sénégal	Université Gaston Berger, ISRA
	Tanzania	ILRI
	Zimbabwe	CIMMYT, University of Zimbabwe

PART B: SYNTHESIS OF MY RESEARCH ACTIVITIES



I. Context

The food security situation in some countries of sub-Saharan Africa has been improving over the past decades, following increases in agricultural GDP (Jayne et al., 2018) fuelling better health (Masters et al., 2018) and nutrition (Beal et al., 2017). Yet, food insecurity is still widespread: for more than a third of households across the continent, available food is below household requirement (Frelat et al., 2016). Food insecurity is a multi-faceted issue, encompassing availability, but also access, utilization and stability. Yet, with the doubling of the population on the continent towards 2050, increase in production and improvement of food availability remains critical to improve food security (van Ittersum et al., 2016). Climate change, and the associated increase in the frequency of extreme droughts and flooding (IPCC, 2021) is likely to constraint the needed increase in crop production (Faye et al., 2018).

Sustainable intensification of crop production on current cropland offers the prospect to contribute to improved food availability and reduced food insecurity (e.g. van Ittersum et al., 2016), while possibly adapting to and even mitigating climate change. Sustainable intensification options include integrated soil fertility management (ISFM, the use of improved cultivar together with mineral and organic nutrient inputs), and diversification with legumes (through rotations or intercropping).

II. Overall research framework

Throughout the past fifteen years, I have been conducting research activities to explore the following research question: What is the likely contribution of sustainable intensification to solving the grand challenges of food insecurity and climate change adaptation in sub-Saharan Africa? Below, I list three important knowledge gaps related to the sustainable intensification of farming systems in sub-Saharan Africa: i) How can sustainable intensification options be tailored to local farmers' contexts? ii) At which conditions (where, for which type of farmer) can these options be scaled at a regional, or continental level and iii) What are the co-benefits of these options in terms of adaptation to climate change?

In what follows, I summarize the contribution of my research to these three critical issues. To do so, I organized my contribution in four research themes:

- i) Understanding the processes explaining the observed benefits of sustainable intensification options
- ii) Understanding the inter-annual variability in the performance of sustainable intensification options and opportunities to mitigate risk
- iii) Incorporating farm-level constraints and opportunities in the analysis of systems' transition towards sustainable intensification
- iv) Assessing scaling opportunities for place-based research results at regional/country level.

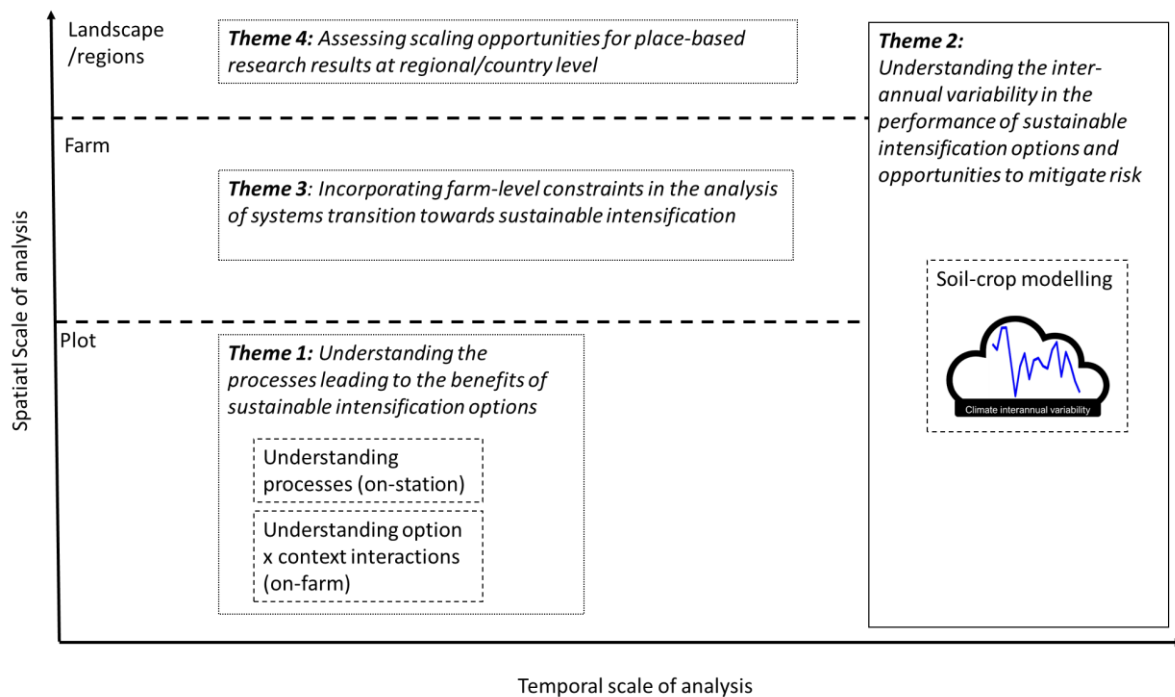


Figure 1: Research themes according to the temporal and spatial scale of analysis

To explore these themes, I have combined a set of analytical methods across scales (plot, farm and landscape/regional) and time (Figure 1). Theme 1 is grounded in the key concept of ‘production ecology’: CO₂, solar radiation and temperature drive potential yield, that can be limited by water and nutrients constraints, and further reduced by pest, weeds and disease pressure (van Ittersum et al., 2013). The extent to which sustainable intensification options that leverage a greater reliance on natural processes (e.g., biological N₂ fixation, improvement in soil organic matter) can help overcome water and nutrient limitations, and help limit weed, pest, and disease pressure, is central to that theme. How farmers’ context influence these natural processes, their relevance and performance (Vanlauwe et al., 2015), is also a key topic within this theme.

Theme 2 builds on the recognition that soil-crop model are useful tools to understand and analyze the complex interactions between crop practices, soil and climate (Affholder et al., 2012). While the research in Theme 1 revolves around the use and analysis of field experiments, Theme 2 aims at extrapolating the findings to larger spatial and temporal scales thanks to the use of the model(s).

Theme 3 is geared towards understanding how farm-level constraints and opportunities influence the benefits generated by sustainable intensification options. The theme builds on the recognition that farms are greatly heterogenous in their resource endowment, objectives and constraints, and that specific tailoring is required (Giller et al., 2011).

Theme 4 aims at mobilizing the ‘recommendation (or development) domains’ theory (Pender et al., 2004) to further explore scaling opportunities for sustainable intensification options identified and tested within Theme 1, 2 and 3. This approach aims at testing the opportunity to use recent tools and datasets (soil-crop modelling, geospatial data) to identify locations where farmers’ circumstances are similar, in order to guide the targeting of specific sustainable intensification options.

III. Main results

1. Theme 1: Understanding the processes explaining the observed benefits of sustainable intensification options

Intercropping cereal with legumes is a critical entry point for diversification of cropping systems. I have studied the performance of cereal-legume intercropping in semi-arid southern Mali and central Senegal (sorghum-cowpea and millet-cowpea intercropping), using factorial, replicated, on-station experiments. Together with PhD students, we found that with additive designs (*i.e.*, the same density of cereal in the intercropping and in the sole crop treatments), the legume competed little in southern Mali (Fig 2A) or not at all in central Senegal (Fig2B) with the cereal. Very often, Land Equivalent Ratios were above 1, indicating a benefit of intercropping (over sole cropping) on land productivity, thanks to complementarities in water and nutrient use between the two crops. The benefits of intercropping decreased with mineral N fertilization in Mali (Figure 2A), in line with finding in temperate cropping systems of industrialized countries (Bedoussac and Justes, 2010).

Testing intercropping in farmers' fields, which I did during my PhD in southern Mali, led to completely different outcomes (Figure 1C). Though some fields displayed similar outcomes compared with what was found on-station (see dots in the upper-left side of the plots), there were many fields where Land Equivalent Ratio (LER) of the intercropping treatment was below one (meaning than less land is required with sole cropping to produce the same yield as with intercropping). There was also some fields where legume grew at the expense of the cereal (see dots in the bottom-right side of the plot in Figure 2C). Such outcomes exemplify the fact that farmer context can strongly influence the performance of a given option. In the same vein, cereal response to fertilizer (and the associated cost: benefit ratio) was highly variable from a field to another (see the example of sorghum on Figure 2D).

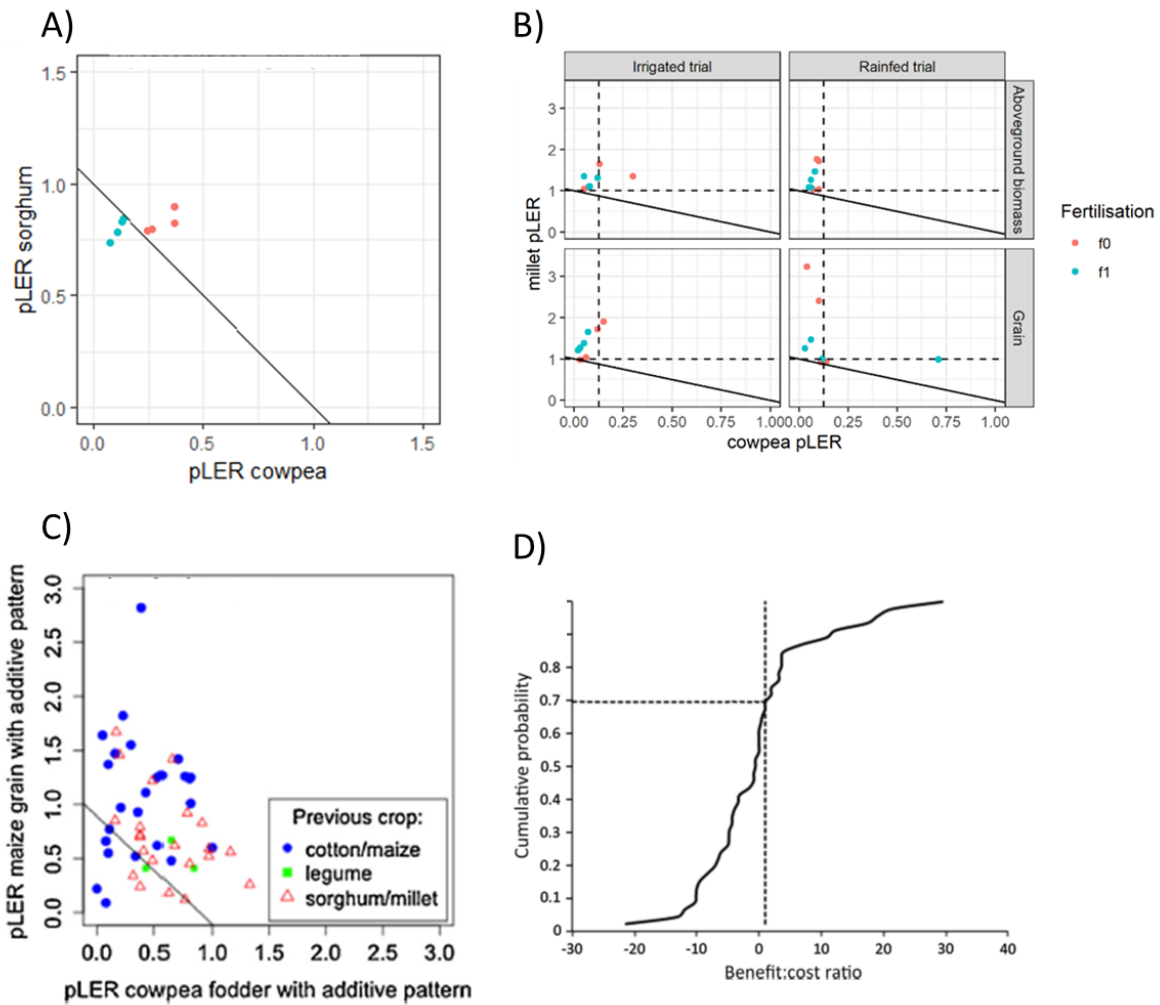


Figure 2: A) Cowpea and sorghum partial Land Equivalent Ratio (intercrop productivity over sole crop productivity, pLER) as observed in the on-station experiment in southern Mali [PA16] (Blue dots are F1, 38 kgN/ha, and red dots are F0, 0 kgN/ha), B) Millet and cowpea pLER as observed in the on-station experiment in central Senegal [PA20] (the horizontal and vertical dotted lines indicate millet and cowpea relative densities in the mixture compared to sole cropping), C) Maize and cowpea pLER as observed in the on-farm trials in southern Mali [PA3], D) Cumulative probability distribution of the benefit/cost ratio of combined mineral and organic fertilizer application (DAP 75 kg/ha and compost 9t/ha) on a local sorghum variety in southern Mali (the dashed lines indicate the probability of achieving a benefit/cost ratio equal to one; Data from 20 to 26 on-farm trials in southern Mali in 2013 and 2014, respectively, the figure was adapted from [PA4]). In A, B and C the black solid line indicates a LER of 1.

This interactions between the performance of sustainable intensification options and farmers' circumstances calls for the identification of option x context combinations. I participated in conceptualizing these so-called 'socio-ecological niches' in a paper during my PhD at the Plant Production Systems group of Wageningen [PA4], and applied the concept in my study case in southern Mali. The analysis of the trial data that I collected during my PhD study (372 trials over four years on a range of ISFM and legume diversification options) demonstrated the critical influence of the previous

crop and soil type on options' performance [PA3]. Farmers mainly apply mineral fertilizer on cotton (their cash crop). As a result, when cotton was the previous crop, soils were usually rich in nutrients, and intercropping behaved in a very similar way as found on-station (*i.e.*, limited competition between the legume and the cereal, with LER generally above one). On the contrary, when sorghum or millet was the previous crop (lower fertilizer applications), soils were less fertile and the legume usually outperformed the cereal (Figure 2C). This understanding allowed to identify, together with farmers, 'niches' for the implementation of these options, *i.e.*, combinations of soil type and previous crop where the agronomic benefits and the profitability of the options were maximized [PA6].

2. Theme 2: Understanding the inter-annual variability in the performance of sustainable intensification options and opportunities to mitigate climate risk

Long-term experiments that deal with sustainable intensification options and the variability of their performance are scarce in the context of sub-Saharan Africa (useful exceptions are *e.g.*, Cardinael et al., 2022; Waddington et al., 2007). Crop models can be calibrated to mimic natural processes underpinning the performance of different options, and then used to explore the impact of climate variability (and possibly climate change) on the performance of these options. For models to be useful, they need to be tested and proven accurate. Existing crop models were generally initially developed for cropping systems in temperate environments and/or cropping systems of industrialized countries that operate near potential crop growth conditions - meaning with limited water and nutrient constraints, thanks to irrigation and adequate mineral fertilizer inputs. These models have been less extensively tested in tropical and 'low input' smallholders' systems. When I joined Cirad in 2018, I was involved in the coordination of an AGMIP activity aiming at evaluating current soil-crop models for simulating maize growth in the context of smallholder farmers in sub-Saharan Africa.

Building on the best available experiments across the continent (*i.e.*, observed in-season soil water, crop leaf area index and biomass) the study [PA12] highlighted i) the large variability in model accuracy when dealing with maize growth, and ii) the critical role of 'full' model calibration based on on-site observations to improve model accuracy and decrease model uncertainty (Figure 3). This study also contributed to further confirm the critical link between climate change and fertilization: the impact of climate change on crop growth will be stronger as farmers intensify crop production with more nutrient inputs. Though this finding already existed in the scientific literature (*e.g.* Affholder, 1997), it was based on an individual case study while our study helped to highlight this interactions for a set of representative sites across sub-Saharan Africa. Of critical relevance for climate change adaptation was also the finding that yield with no N input were lowered in wetter years due to leaching of the precious mineral N originating from soil organic matter mineralization.

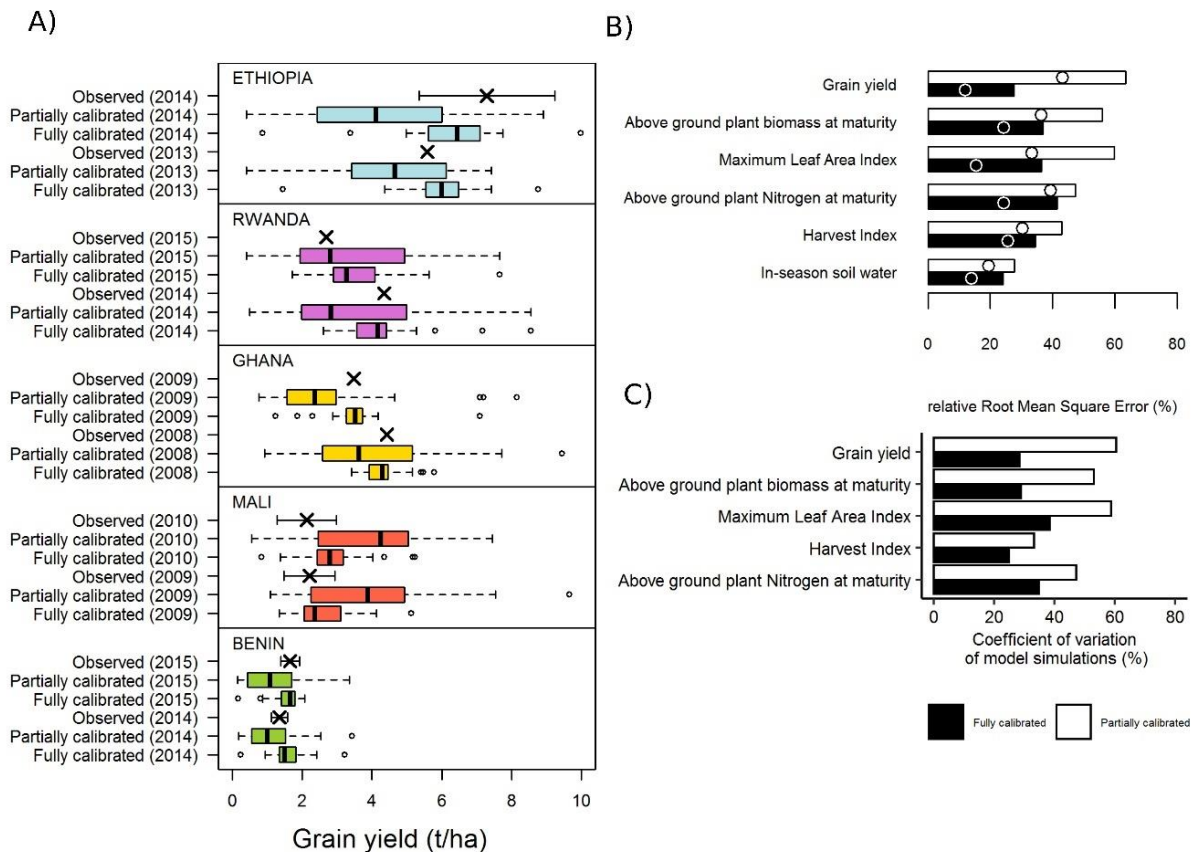


Figure 3: (A) Observed (crosses with standard deviation if known) and simulated (box plots) grain yields at five representative experimental sites in sub-Saharan Africa. Simulations are from an ensemble of 25 partially and fully calibrated models. Black open dots are outliers. (B) relative Root Mean Square Error (rRMSE, averaged across all models) of simulated – observed comparison for six variables of interest. For aboveground plant nitrogen the comparison was possible for four of the ten experiments only (Benin and Ghana). Open dots indicate rRMSE of ensemble median. (C) Coefficient of variation (averaged across sites) of 25 model simulations for five variables.

The extent to which crop models have been tested and improved depends on the sustainable intensification option under consideration. Studies abound on the simulation of the impact of i) improved varieties (e.g., with shorter duration or contrasting sensitivity to photoperiod) and ii) contrasting N input use. Diversification with legumes (e.g., through cereal-legume intercropping or rotation with green manure) and integrated soil fertility management (ISFM, combination of mineral and organic inputs) have attracted less scrutiny. Because my research has focused on the impact of these options in the face of climate variability, I dedicated a substantial amount of my research activities to test crop models on their ability to deal with legume integration into cropping systems and ISFM. I contributed to demonstrate the ability of the STICS soil-crop model to accurately simulate the performance of a range of legume options (Figure 4). STICS was able to simulate the impact of water stress on nitrogen fixation, and this turned-out to explain a large part of the observed variability in N_2 fixed by fababeans in southern France (Figure 4A, [PA8]). The model also proved useful in reproducing the impact of green manure incorporation on rice N uptake in the sub-humid highlands of Madagascar (Figure 4B, [PA17]). The impact of intercropping sorghum with cowpea on land productivity in southern Mali was also well reproduced by the intercropping version of the STICS soil-crop model (Figure 4C,

[PA16]). STICS was also robustly calibrated for millet in Senegal, and, though not validated with observations, could be of value to explore the impact of *Faibherbia* parklands on millet growth [PA28].

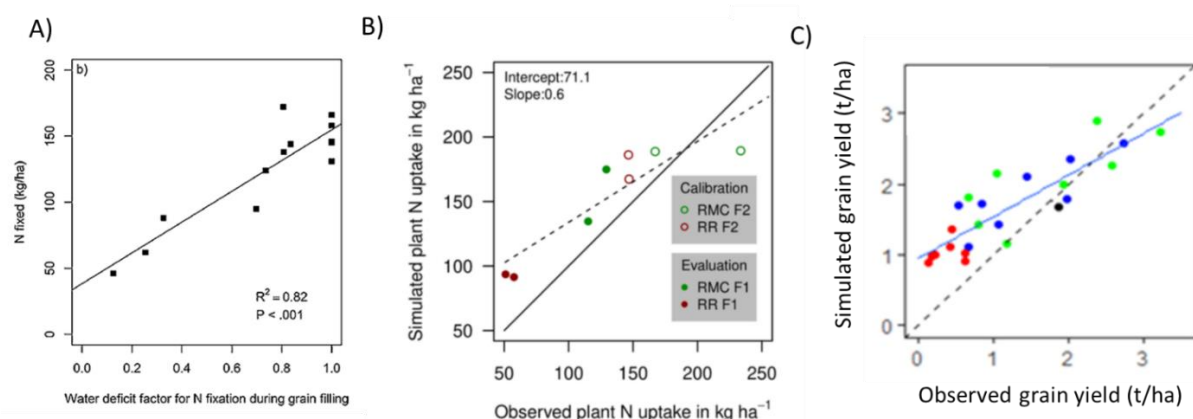


Figure 4: A) Observed N_2 fixed at harvest by fababean (on-station experiments in southern France) and simulated water deficit factor for N_2 fixation during grain filling [PA8], B) Observed and simulated plant N uptake at flowering according to residue type and level of fertilization in Madagascar [PA17], and C) Observed and simulated grain yield in a sorghum/cowpea intercropping experiment in southern Mali [PA16] (green dots are sole sorghum, blue dots are intercropped sorghum, the black dot is sole cowpea, and red dots are intercropped cowpea).

With regard to ISFM, we showed that current models could accurately reproduce long-term changes in crop yield and soil organic carbon, provided that observations were available for local calibration [PA24]. This AGMIP model intercomparison [PA24] showed that uncertainty in predicting long-term change in soil organic carbon increased over time, due to uncertainties in simulating i) root inputs to the soil and ii) mineral N provision by the mineralization of soil organic matter and organic amendments.

Thanks to these efforts on model calibration in relation to diversification and ISFM options, I was able to contribute to building and running virtual experiments that yielded critical insights onto the opportunity to use these options to build resilience against climate change. Surprisingly, diversification with legumes did not appear to be a silver bullet for more resilience to climate variability of cropping systems: i) nitrogen leaching undermined the benefits of the incorporation of green manure in Malagasy sub-humid highlands (Figure 5A, [PA17]), ii) intercropping only marginally stabilized yield when nutrient inputs were added in semi-arid southern Mali (Figure 5B, [PA23]), iii) the benefits of intercropping (as expressed by maize pLER) were found to significantly diminish when water stress was stronger in semi-arid Zimbabwe (Figure 5C, [RA5]). Nevertheless, legume remain a key opportunity for farmers. Simulations in sub-Humid Zimbabwe have shown that the frequency of sub-optimal productivity (i.e. below 70% of maximum yield) was much lower for intensification of groundnut production (with better weed, pest and disease management) compared with intensification of maize production with mineral fertilizer (Figure 6, [RA9]).

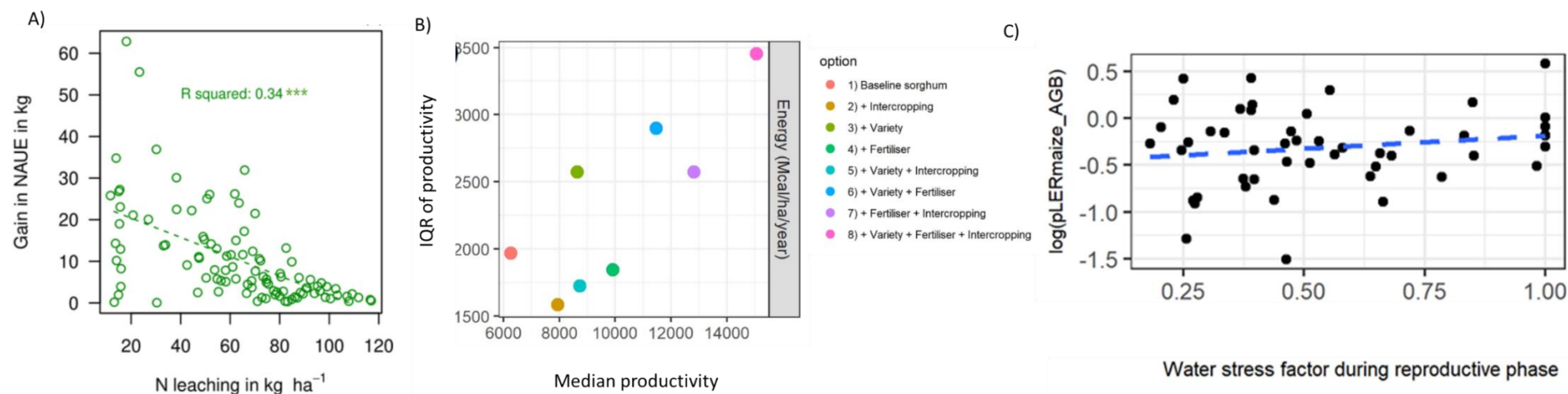


Figure 5: A) Gains in rice Nitrogen Agronomic Efficiency (NAE) due to green manure incorporation compared to rice residue incorporation, as a function of N leaching for 25 simulated rice growing season in Madagascar highlands [PA17], B) Median and Inter Quartile Range (IQR) of productivity (for energy) of eight sustainable intensification options in southern Mali [PA23], C) Relations between pLER of aboveground biomass (AGB, log transformed value) for maize against simulated water stress averaged during reproductive phases in semi-arid Zimbabwe [RA5].



Figure 6: Simulation of 27 seasons of water and nitrogen-limited yield for groundnut and maize fertilized with 80 kgN/ha (plain line) in sub-humid Zimbabwe [RA9]. Dashed line is the maximum water and nitrogen-limited yield over the 27 seasons (Y_{max}). The grey shaded area indicates yield above 70% of Y_{max} .

On the other hand, more 'conventional' practice like adequate varietal choice, proved to be a useful strategy for adaptation, for example shifting from spring to winter legume in southern France [PA9] or using longer duration rice cultivars and cultivar adapted to temperature stress in Senegal [PA13].

3. Theme 3: Incorporating farm-level constraints and opportunities in the analysis of systems' transition towards sustainable intensification

Farms across SSA are highly heterogenous in terms of resources, land and labour productivity, objectives and constraints (Figure 7). Resource endowment and land productivity is very often tightly connected, as exemplified by the case of cotton farmers in southern Mali (Figure 7A, [PA2]). Yet, similar land productivity can mask contrasting labour productivity and food self-sufficiency, due to contrasting land/labour ratio (see MRE and HRE farms on Figure 7A). In Tanzania, a nationally representative household survey shows the tremendous variability in food availability (Figure 7B, [PA21]). Crops produced and consumed on-farm were the largest contributors to household food availability for food insecure households in Tanzania. In Uganda, a similar analysis showed that it was off-farm income and sales of livestock and crop products that contributed more to the food security status of farm households (data not shown).

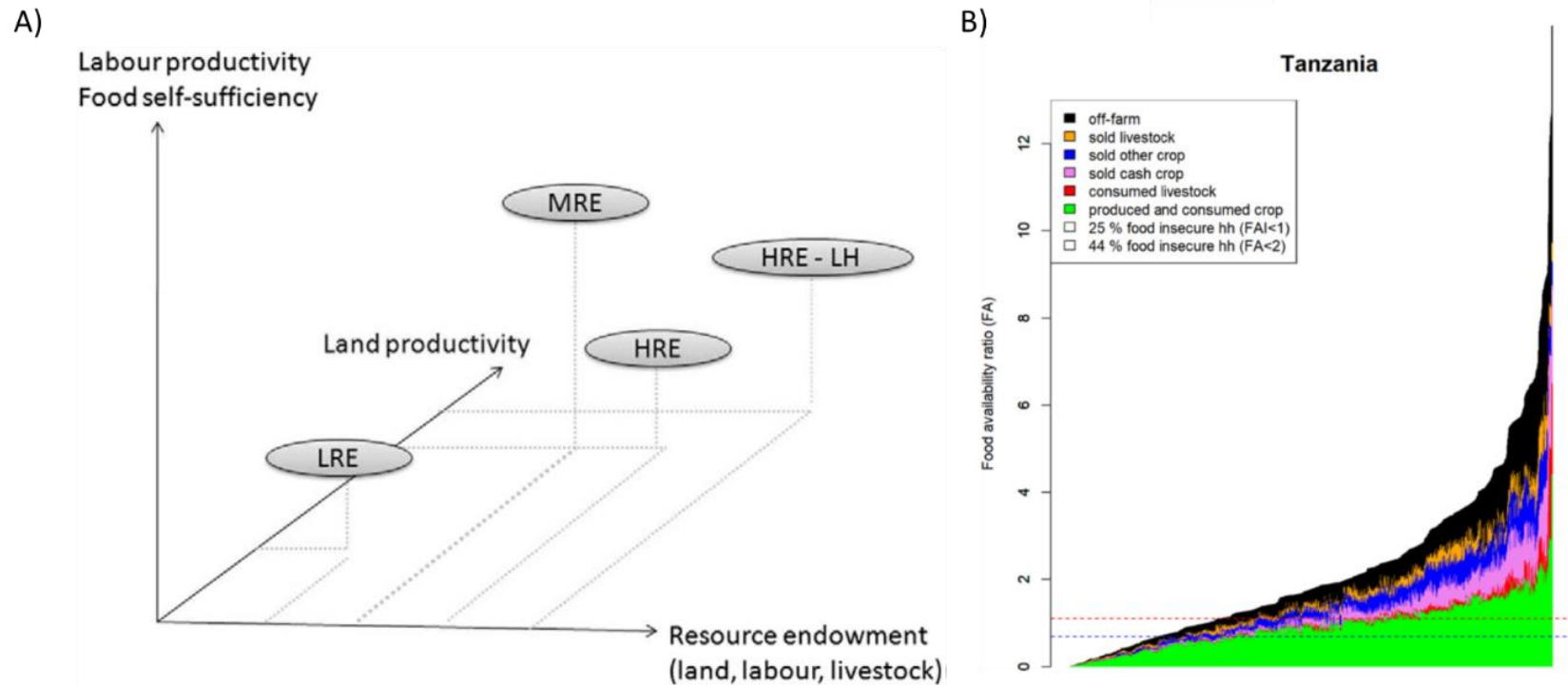
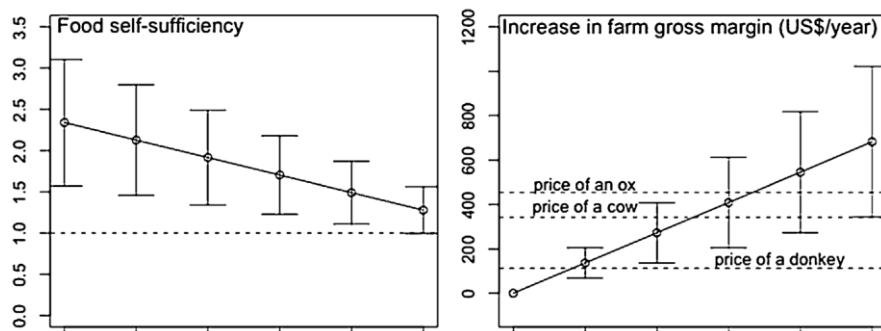


Figure 7: A) Conceptual representation of four farm types in a three-dimensional space of resource endowment, land productivity and combined labour productivity and food self-sufficiency, based on a panel survey that monitored 30 farms in the Koutiala district in southern Mali from 1994 to 2010 [PA2], B) Household (hh) food availability ratio (FA) for 2435 households in Tanzania [PA21]. The y-axis was log-transformed so that $y = \log(FA + 1)$. Households were ordered by increasing food availability ratio (i.e., the ratio of available food to the required food) along the x-axis. A bar is one household. The red dashed line is the 5000 kcal/capita/day food security threshold (i.e., food availability ratio = 2), and the blue dashed line is the 2500 kcal/capita/day food security threshold (i.e., food availability ratio = 1). A rolling average was applied with subsets of 30 households to smooth the curves for easier interpretation. Different colours indicate the source of the food, be it produced on-farm or purchased. Crops were considered as cash crops when >90% of the annual production was sold. Large values of sold and consumed crop on the right side of the plots correspond to potential bias in survey data rather than to real consumption values.

I contributed to highlight the critical need to account for household resource endowment, objectives and constraints when looking at the integration of sustainable intensification options into farming systems. Looking at the example of farming systems in land-constrained southern Mali, I explored the impact of cropland diversification on food self-sufficiency and income, using the performance of the options as quantified through on-farm trials (see previous section), and an ex-ante farm analysis [PA6]. The ex-ante analysis was built around a very simple farm model that computed farm food self-sufficiency and income, based on the productivity and the profitability of the crop and livestock options that were implemented by the farmers. I found that low resource-endowed farms could not replace more than 40% of their sorghum area by soybean without compromising their food self-sufficiency status (Figure 8). With such a diversification strategy (towards high-value soybean), the increase in income equated the cost of a donkey (Figure 8, [PA6]). On the contrary, medium resource endowed farmers would be able to replace 100% of their sorghum by soybean, without compromising their food self-sufficiency. This would lead to greater increase in income (equating the cost of an additional ox, an asset very critical for land preparation in the area). A similar options therefore yielded contrasting opportunities for different farm types to climb the ‘livestock ladder’ (Udo et al., 2011).

MRE



LRE

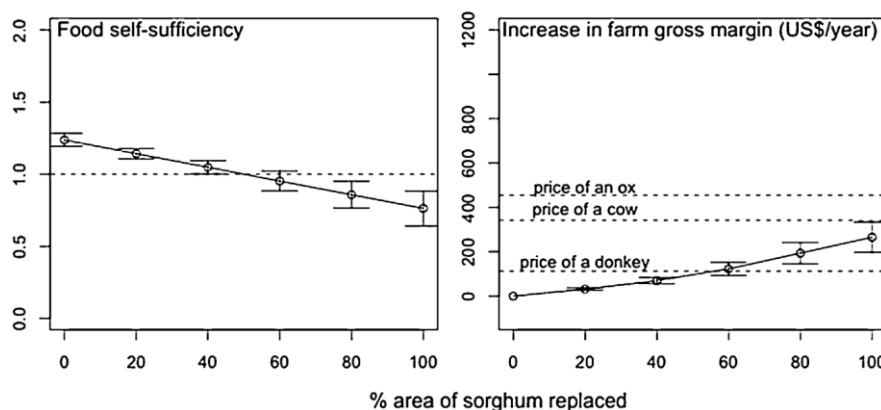


Figure 8: Effects of replacing sorghum on selected farm performance indicators, resulting from the ex-ante trade-off analysis for Medium Resource Endowed (MRE) farms ($n=2$) and Low Resource Endowed (LRE) farms ($n=4$) in southern Mali. For MRE farms, sorghum is replaced by soybean on black soils after cotton and maize, for LRE farms sorghum is replaced by cowpea grain variety on gravelly or sandy soils. Vertical bars represent twice the standard error of the mean. The horizontal dashed line in the “Food self-sufficiency” plots represents the food self-sufficiency threshold of one, meaning all household energy needs are provided by the household’s own cereal production.

In the eastern African context, I led a food availability analysis based on a nationally representative set of households across Tanzania and Uganda, and a model for spatial prediction of maize response to fertiliser. The analysis showed that intensification of maize production with more mineral fertilizer benefited more (in terms of increasing food availability, FA) food deficient and food fragile households ($FA < 2$) than already food secure households ($FA > 2$) (Figure 9, [PA21]).

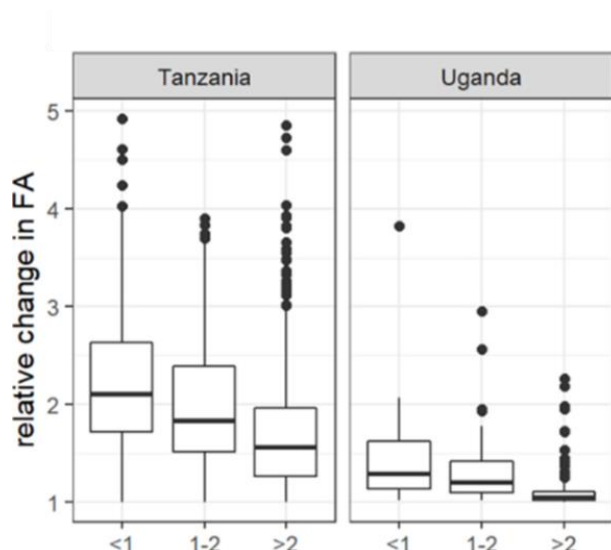


Figure 9: Boxplots of relative change in Food availability ratio (FA) with the use of profit-maximizing mineral fertilizer, disaggregated per FA class in Tanzania and Uganda. The boxplots show the variability of the impact of Food availability across the surveyed households (2435 households in Tanzania and 1753 households in Uganda).

These two examples show the critical need to consider farm level constraints when dealing with sustainable intensification. While plot-level outcomes (e.g., yield, gross margin) can be substantial, a farm-level analysis often concludes on very limited benefits. This is further exemplified by the example of the cotton area in southern Mali, where a very ambitious transition for all farmers to 100% intercropping of maize with legume, and stall feeding of dairy cows with the fodder produced on-farm, only marginally improved farmer income and food self-sufficiency. Figure 10a and 10b [PA7] compares the baseline situation with this ‘dairy development’ scenario: a substantial share of the farm population remains food insecure and below poverty line. Socio-economic development (e.g., family planning and job creation outside agriculture, see Figure 10e), and possibly ambitious narrowing of yield gap (Figure 10f), are required to lift to entire farm population above the poverty line.

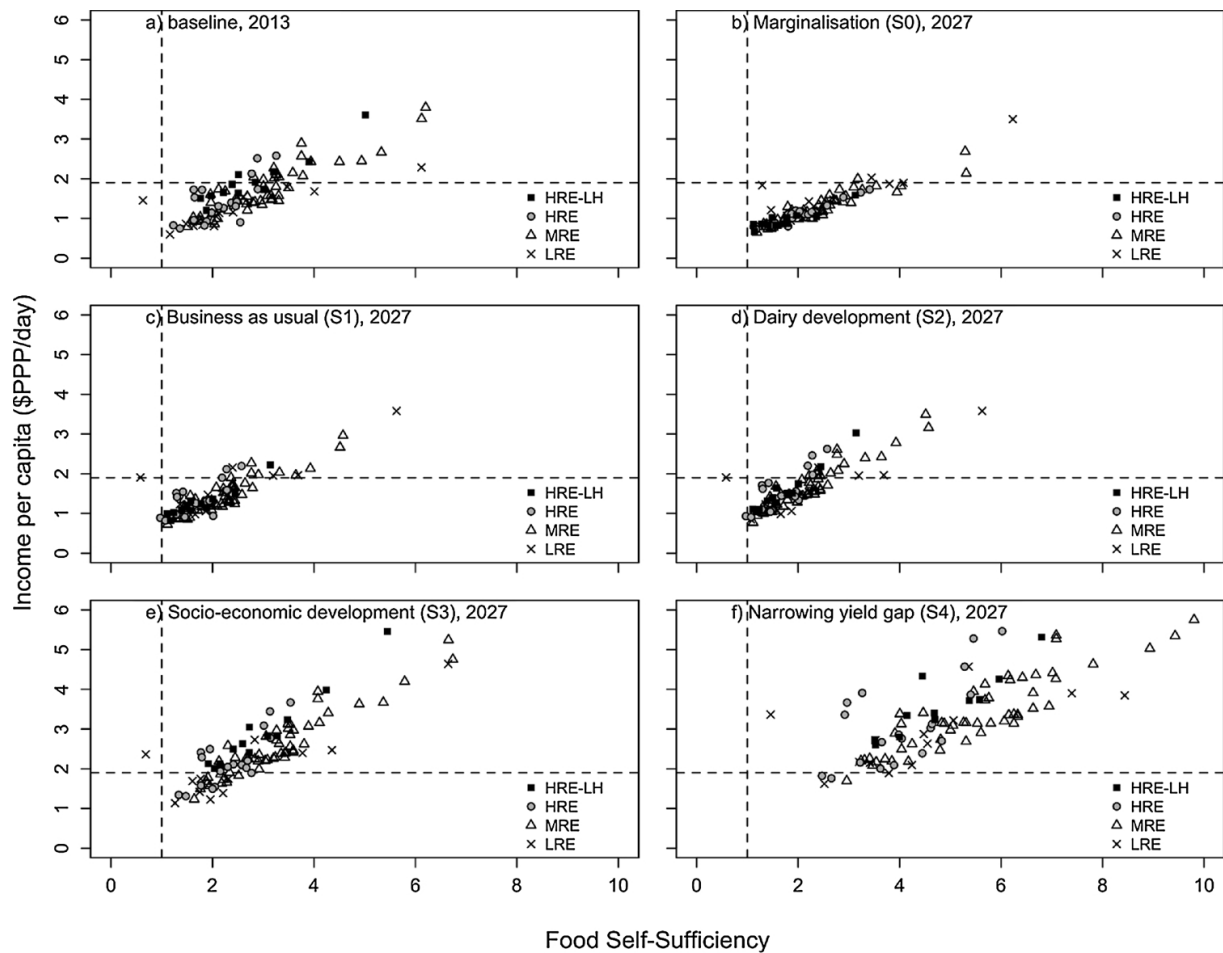


Figure 10: Food self-sufficiency ratio and income per capita of the 99 households of Nampossela village in southern Mali in 2013 (a) and 2027 for different scenarios of agricultural intensification and policy intervention (b, c, d, e, f) for an average rainfall year (734 mm). The horizontal and vertical dotted lines represent the 1.25 \$PPP/day poverty line and the food self-sufficiency threshold, respectively.

Another key aspect when dealing with tailoring sustainable intensification options to the context of farmers, is the need to consider relevant metrics for assessment. Farmers value some criteria that need to be accounted for, e.g. autonomy, health, work drudgery [PA10]. Also, the assessment needs to go beyond average performance, because good ‘average’ performance can hide poor performance in some years (e.g. Figure 6). Furthermore, this assessment needs to cover the agronomic, but also environmental and economic dimensions. These aspects were reflected in a recent review of literature on the evaluation of ‘resilience’ at the farm level, led by PhD student Valentin Pret [PA29].

4. Theme 4: Assessing scaling opportunities for place-based research results at regional/country level

The studies presented in the previous sections highlight the highly contextual performance of sustainable intensification options (e.g., soil type, past crop management, climate and farm type). Yet the information is fragmented in terms of spatial coverage, so that the potential to derive the large-scale messages that are of interest for decision makers is limited. In order to address this challenge, I developed, or got involved into, a set of studies that try to make use of point-based findings to generate larger scale recommendations.

Complementing a rich dataset built by Bonilla Cedrez et al. (2021) on maize response to fertiliser (15,952 observations), I contributed to build a random forest model that can predict maize response to fertiliser as a function of soil characteristics (Figure 11A, [PA21]). This model was used to explore the impact of maize intensification on household food security for a nationally-representative set of households in Uganda and Tanzania (Figure 11B, C, [PA21]). The analysis, accounting for both soil and farm type constraints, showed that i) a substantial increase in national maize supply was more likely to come from already food secure households with relatively large farms, while food insecure households with small farms would nevertheless increase their household-level food security through maize intensification, and ii) high potential areas to increase maize domestic production did not necessarily match with areas where there was immediate scope to improve household-level food security (Figure 11B, C, [PA21]).

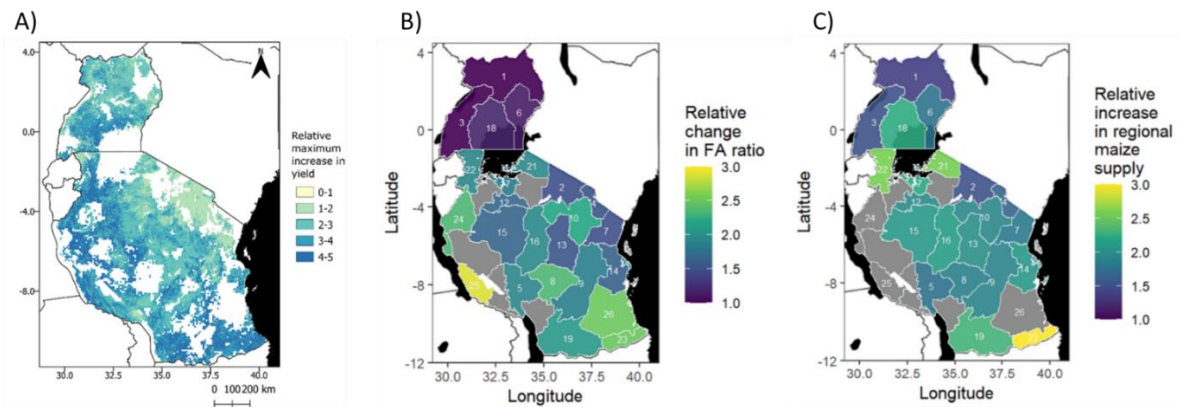


Figure 11: A) Maximum relative increase in yield (i.e., yield with maximum (200 N/20P/20 K) fertilizer application divided by control yield) as predicted by the random forest model (areas in Uganda and Tanzania where maize is not grown, according to IFPRI, 2020, appear in white). B) map of regional median relative change in food availability ratio for food insecure maize-growers, and C) map of relative increase in regional maize supply.

One pitfall of the machine learning model was its low sensitivity to inter-annual variations in rainfall, precluding the analysis of the risk associated with the use of mineral fertiliser (i.e., low response in some dry years). Dynamic soil crop models can be useful to analyze and simulate this variation in inter-annual response to fertiliser. In that direction, we have been developing a platform for multi-model simulation and spatial exploration [PA25].

I also contributed to a study aiming at simulating the spatial variability of millet production in the context of *Faidherbia albida* parklands in central Senegal [PA11]. Trees influence crop growth, but the current large-scale estimates of crop production based on remote sensing very often overlook this contribution. We showed that adding parkland structure information to the vegetation productivity remote-sensed signal improved greatly the accuracy of a machine learning model aiming at predicting millet yield. Model predictions allowed the computation of millet yield gap for a small region (Figure 12A, [PA11]), and the identification of landscape woody cover as a critical contributor to better millet yield (Figure 12B, [PA11]). This finding highlights the critical role of landscape configuration as an sustainable intensification option.

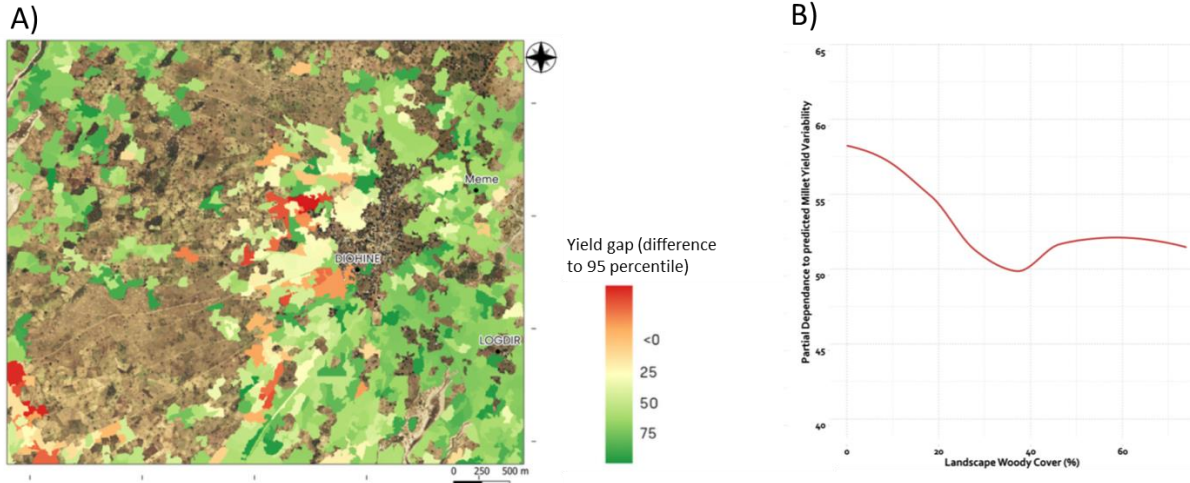


Figure 12: A) Millet yield gap (%difference to the 95th percentile) over the study area at patch scale using remote sensing information, B) marginal effect (partial dependence plot) of woody cover in surrounding landscape of millet patches on predicted yield gap.

The above-mentioned studies in Uganda, Tanzania and Senegal rely on a soil digital map for the spatial exploration of the impact of sustainable intensification options on crop productivity – namely Africa SoilGrid (Hengl et al., 2017). This type of soil map is very useful, yet it sometimes miss some critical local relevance. I contributed to one study that describes some avenues to improve these maps [PA18]. We showed the opportunity to augment the training datasets of the models used for interpolation of soil data. Soil measurement for homosols, *i.e.*, locations sharing similar soil-forming factor, can be used for model training and improve model accuracy over a case-study area that can be far away from the homosols.

In another study [PA19], we identified favorable areas in west Africa for the uptake of a set of sustainable intensification options (cereal-legume intercropping, fodder legume cultivation, farmer managed natural regeneration (FMNR) of *Parkia biglobosa*, and crop residue mulching). The mapping was based on biophysical (e.g., rainfall and landcover) and socio-technical (e.g., population and livestock densities) variables. The originality of the work was the incorporation of institutional variables in the analysis (e.g., adaptation plans and nationally determined contribution at country level). This analysis allowed to delineate favourable and unfavourable areas where biophysical, socio-technical and institutional variables aligned, e.g., southern Mali for intercropping.

PART C: PROJECT PROPOSAL

I. Introduction

My past research activities have provided evidence of where and how plot-level sustainable intensification options could benefit smallholder farmers, given insights of some of the farm-level barriers and opportunities for wide adoption, and initiated the identification of scaling opportunities at regional level. Yet the evidence is still fragmented, some options being more investigated than others, or a scale of analysis being more thoroughly studied. This preclude the generation of clear message that could guide priority setting and scaling of agricultural intensification technologies and investments in sub-Saharan Africa.

The Cirad-AIDA research team, to which I belong, has been conducting numerous place-based studies, which are well documented and highly relevant to guide local decision making. However, the contribution of such studies to informing global sustainability issue is unclear, i.e., would the findings be applicable to large swatch of SSA (how many hectares?), and/or to significant number of households (how many millions?). For example, soils might be unresponsive to nutrient applications, and case studies documenting this challenge at various sites in SSA abound (e.g., Kihara et al., 2016; Njoroge et al., 2017). However, how widespread these type of soils are across Africa, and how many rural households are affected, is unknown, as is the extent to which this is going to impact the potential to increase food availability on the continent. Similarly, green manure and cover crops have been proven useful in reducing the need for mineral fertilizer at contrasting sites in semi-arid and sub-humid areas of SSA (e.g., Ojiem et al., 2014; Ripoche et al., 2021). But would the adoption of this practice by majority of farmers bring down the negative aggregated impacts of fertilizer on the environment in a substantial way?

1. Challenges and opportunities to scale plot-level findings

These typical questions are being answered by the research community with top-down and bottom-up approaches (Grassini et al., 2017). The 'top-down' approach makes use of globally available geodata (on e.g., soil, climate, crop area) to infer local outcomes (e.g., crop productivity, environmental risk). Conversely, the bottom-up approach starts with a local understanding of systems' behavior using a set of spatially representative locations, that is then extrapolated for the zones that share similar characteristics with the locations used for the local understanding (soils, climate, distance to market, population density).

Typical 'top-down' studies have looked into the impact of climate change on maize, rice, wheat, and soybean, worldwide (e.g. Jägermeyr et al., 2021), with the use of ensembles of global gridded crop models (e.g. Franke et al., 2019). These studies often have very limited local relevance because of limited (if not any) local calibration of the models used to perform the explorations. These uncalibrated 'top-down' approaches incorporate a great deal of uncertainty that can undermine the recommendations generated (Rattalino Edreira et al., 2021). For example, a careful look at the outputs of Global gridded models shows that no response to nitrogen input on coarse sandy soil of southern Mali, where strong response is actually expected and observed, or maize yield up to 6 t/ha in areas of western semi-arid Kenya where maize cultivation is barely possible. While these global gridded crop models are of no doubt of great use to inform sustainability issues at the global scale and/or cross-continental comparisons, they will fall short at providing the robust estimates that are required to prioritize and guide investments for sustainable intensification on the African continent. Furthermore,

these explorations have only incorporated, to date, the impact of improved variety and (rarely) fertilizer input. Other sustainable intensification options that rely on diversification and integrated fertility management (e.g., intercropping, green manure, agroforestry, compost) have not been dealt with.

A typical bottom-up study has explored the potential to store more carbon with cover crop at the scale of France, with the use of a well-tested and calibrated crop model using more than 1800 cropping situations across the country (Launay et al., 2021). The authors found that including cover crop could mitigate 50% of cropping systems emissions at the scale of the country. This type of bottom-up approach is critically missing when it comes to a set of sustainable intensification options – in particular for the case of sub-Saharan Africa. I am eager to put my energy to contribute to fill this knowledge gap, making use of CIRAD's large breadth of field data and the strong knowledge of my research group on crop modelling.

2. Challenges and opportunities to scale farm-level findings

The household level is critical when looking at sustainable intensification, because constraints and opportunities operate beyond the field level e.g., competing labour demand for farm activities, opportunities arising from the availability of off-farm income for some farm types. Mapping the diversity of farm types is challenging, as local diversity in a specific location often outweighs country-wide variations (Wichern et al., 2018). Rather than aiming at continuous spatial prediction of farm characteristics (as done for crop-level outputs), the research community has been relying on nationally representative household surveys that help understand variations in household characteristics (Frelat et al., 2016; Giller et al., 2021). This has been allowed by recent joint efforts to harmonize and compile household data across several countries and locations in Africa [e.g., the Living Standard Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA), Kilic et al., 2015, The Rural Household Multi-Indicator Survey (RHoMIS), Hammond et al., 2017]. These large household datasets have been leveraged to evaluate, ex-ante, how closing the yield gap (both for crop and animal production) could help improve food security (Paul et al., 2017; Ritzema et al., 2017) and how this is impacted by farm size and other characteristics such as off-farm income. These studies have not dealt extensively on the practices that are required to close the yield gap, and have not looked into details of whether land, labour, or cash, were key constraints. They also don't include a thorough analysis of the type of policy incentives that are needed to help farmers solve labour and cash constraints.

Another type of study relies on more detailed farm surveys (that describes farm activities throughout the year) and more complex models, e.g. bioeconomic models. These models incorporate a set of equations to describe farmers constraints (cash and labour flow in different periods of the year, suitability of land for certain crops) and objectives (e.g., subsistence, maximizing farm income). Production functions define the productivity of crop and livestock activities. The model then relies on an optimization algorithm to determine the crop allocation that meets the objectives of the farmer. Comparison between simulated and observed land allocation helps to refine model calibration (e.g., the productivity or labour requirement of a given activity, the price of a given input). This type of model has been successfully used to analyse how a set of contrasting policy incentives (direct cash transfer, subsidy for mineral fertilisers, crop insurance) would trigger the adoption of integrated soil fertility management practices in central Senegal (Gérard et al., 2020; Ricome et al., 2017). The studies have pointed to critical trade-off between income and environmental indicator (e.g., N erosion) when

implementing standard innovative practices, pointing to need for policy incentives if more sustainable (but less economically attractive) practices are to be implemented (Lairez et al., 2023). Though very useful in understanding trade-offs at farm level, these detailed studies relying on bioeconomic modelling have remained rather limited in geographical scope with no comparison between countries and/or agroecological zones. There is thus a need for a hybrid approach, that leverages both coarse but large and nationally-representative household datasets, and detailed household characterization (with farm typologies and in-season resource flows) at a few representative sites. A key focus will be how different farm types respond to a change in the broader socio-economic context. The key question then is whether intra-site diversity in that response is stronger than the diversity between sites.

3. Incorporating landscape considerations

Field and farm level analysis overlook key aspects related to natural resource governance and collective action that take place at the landscape level. To be applicable, field-level sustainable intensification options require a set of collective rules that apply at the landscape level. A typical example is crop residue mulching, that is only feasible if farmers fence their fields. Cattle of neighbouring farms can no longer graze in these fenced fields during the dry season – hence the need for concertation among farmers, and possibly production of fodder during the rainy season. Non-cattle farmers may want to fence their field to keep their crop residues rather than have them grazed by farmers owning cattle – which means for these non-cattle farmers losing an opportunity to replenish the fertility of their fields (Rufino et al., 2011). Such equity issues can only be understood when the landscape level is considered.

Field and farm level analysis also overlook the importance of landscape composition and configuration on the performance of some sustainable intensification option. For example, the field-level performance of push-pull cannot be fully understood if landscape composition and configuration is not accounted for. Push-pull is a technology consisting of i) intercropping cereals with a legume that repels stemborers (the ‘push’), and ii) growing a fodder crop around the plot that attracts the pests (the ‘pull’). Kebede et al. (2018) showed that push-pull worked well in landscape of intermediary complexity, but was not useful for crop protection in more complex landscapes, because the natural predators were already abundant and pest pressure low.

Landscape is also a very useful scale of analysis when dealing with biodiversity conservation. For example, producing more biomass with intercropping cereal and legume and stall feeding of livestock offer the potential to reduce livestock pressure on savannah rangeland, possibly increasing the quantity and quality of natural habitats for wildlife. Biodiversity-rich landscapes, through providing ecosystem services [e.g. carbon sequestration (Berzaghi et al., 2022), pest regulation (Sow et al., 2020)], can also cause a range of disservices such as human-wildlife conflicts, crop damages, and spread of diseases to livestock. The extent to which landscape reconfiguration (e.g. livestock corridors, conservation areas, mosaic to favour natural predators) and specific field-level practices can help mitigate these conflicts need to be scrutinized. Biodiversity conservation is a critical challenge to consider when dealing with sustainability, yet I have mostly overlooked it in my past research – incorporating the landscape level into my future research framework offer the opportunity to fill that gap.

II. A research framework for a multi-level assessment

Following this analysis of key research and methodological gaps at crop, farm and landscape level, my research project for the coming years will be ‘a multi-level assessment of sustainable intensification options contribution to food security, climate change adaptation and mitigation, and biodiversity conservation’. I will explore the three following research questions:

- i) **How does spatial and temporal variation in climate and soils drives the agronomic and environmental performance of sustainable intensification options?**
- ii) **What are key trade-offs for resource allocation at farm level (cash, labour, land) that impede the large implementation of sustainable intensification options, and how does this vary locally (farm type) and more broadly across the continent (agroecological zones)?**
- iii) **Which landscape composition and configuration are required to reconcile food security, climate change mitigation and adaptation, and biodiversity conservation?**

Central to these questions is the identification of policy interventions and incentives that would help alleviate identified farm and landscape level trade-offs. To help answer these questions, I propose a framework that articulates the three levels of analysis, namely the field, the farm, and the landscape (Figure 13 and Figure 14). The overall aim of the framework is to produce realistic estimates of the performance of sustainable intensification options at plot-level, provide evidence of barriers and opportunities (with a focus on policy incentives) for their implementation in the farm, and assess how this aggregates at the landscape level in terms of food security, climate change adaptation and mitigation, and biodiversity conservation.

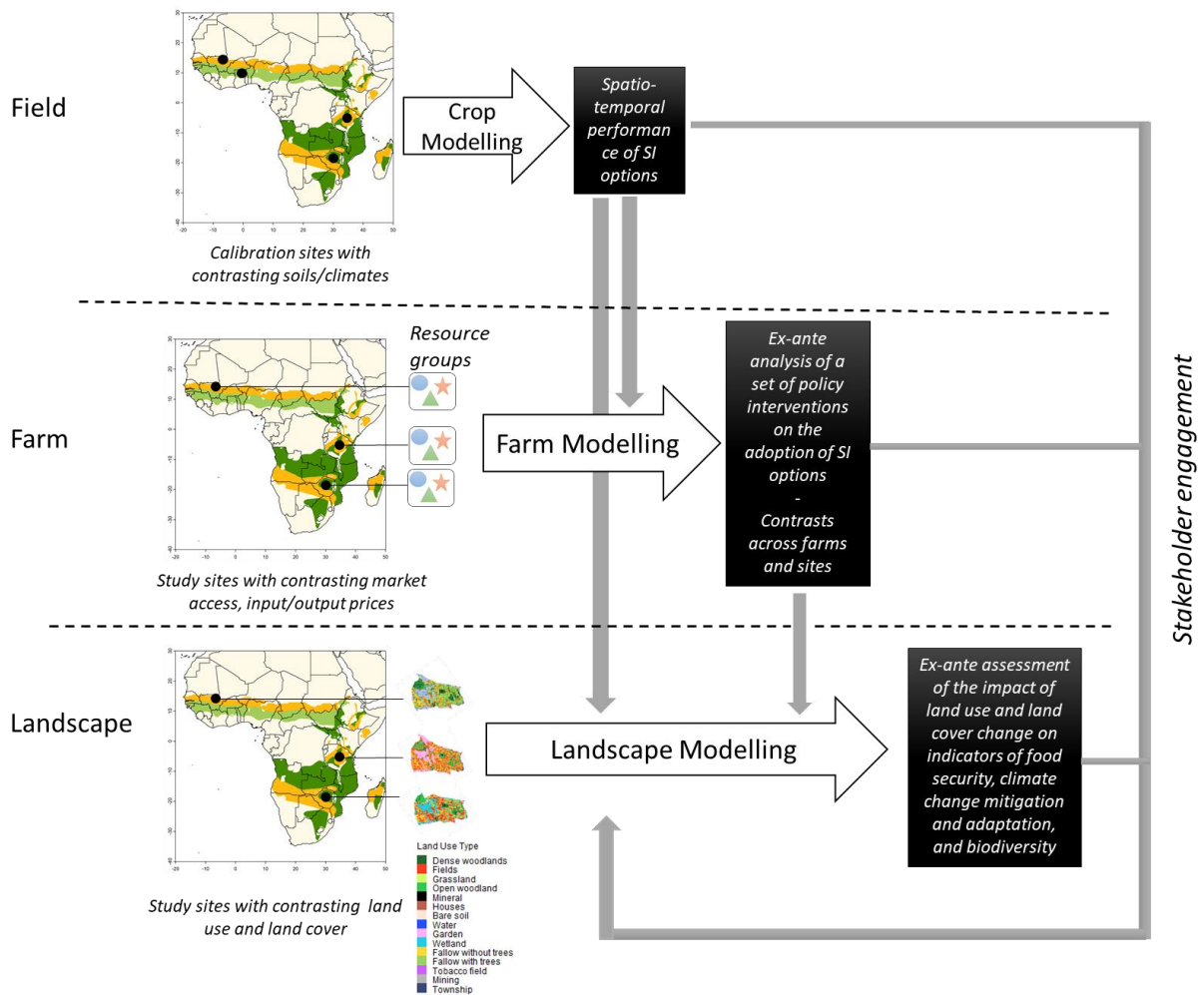
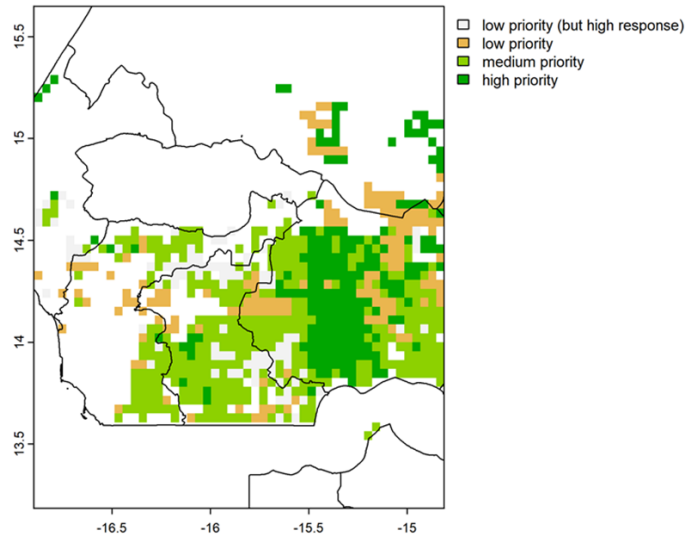
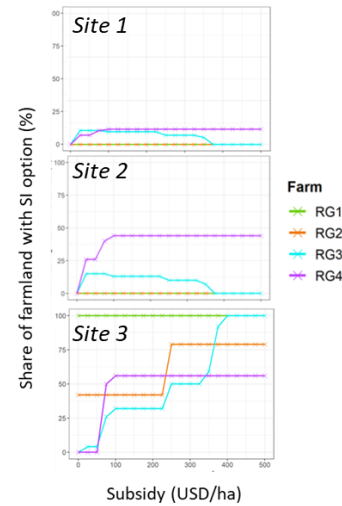


Figure 13: Framework for the multi-level (field-farm-landscape) analysis of the impact of sustainable intensification options on food security, climate change adaptation and mitigation, and biodiversity conservation. Black dots are study sites for data collection and model refinement. Coloured rounds, stars and triangles are possible contrasting farm types at the study sites.

A) Field



B) Farm



C) Landscape

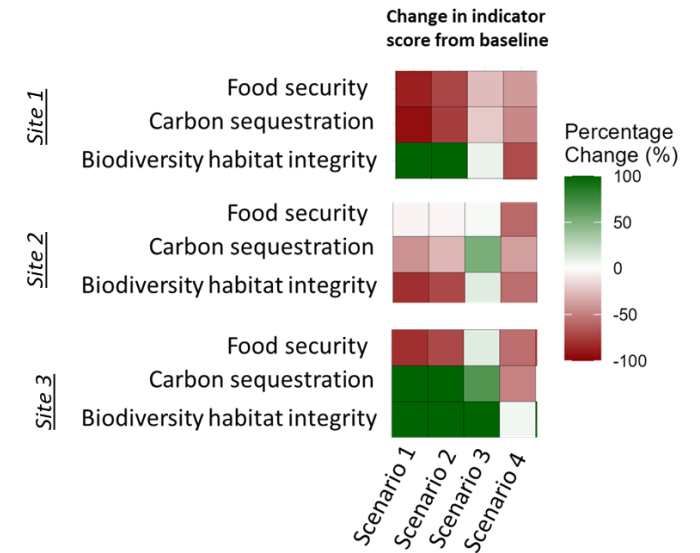


Figure 14: Typical outputs of the analytical framework at field (A), farm (B) and landscape (C) levels. Figure 2A is extracted from [RA4], Figure 2B is adapted from the Master thesis of L. Brun Berger (see part A) and Figure C is adapted from [RA14]. SI: Sustainable Intensification.

In what follows, I describe some of the key elements of this framework.

1. Study/calibration sites

Strong emphasis is put on the reliance on ground observations at contrasting calibration and study sites ('bottom-up' approach). Field-level calibration sites need to span across a wide range of climatic conditions (rainfall, temperature) and soil types (texture, nutrient content). When looking at the farm-level, while climate and soil still matters, specific attention needs to be given to external socio-economic factors such as e.g., the current prices of farm outputs and cost of farm inputs, the distance to market. Farm typology that define contrasting resource groups help understanding the within-site farm diversity. At the landscape level, contrasts in landscape-related metrics are sought, e.g., the share of cropland, grazing land in the landscape, the configuration of woody patch, landscape connectivity.

2. Analytical tools

The analyses that are carried-out rely on modelling. The data gathered on-site help with the calibration of crop, farm, and landscape models. The use of a given type of model is by no means fixed, and always chosen with regard to the objective (Affholder et al., 2012). At plot level, dynamic and process-based crop models are suitable, but machine learning models also offer opportunities when spatial prediction is the objective, and not necessarily a thorough understanding of the processes at stake. The local data is used to understand pitfalls in current models, where they fail and where more data collection is required for improvement – something that is not allowed in a mere 'top-down' approach. At farm level, bio-economic models are a useful tools, but simpler index and calculation can also be mobilized (e.g., the food availability index, as in Frelat et al., 2016, and [PA21]). At landscape level, ad-hoc models that incorporate the impact of land use and land cover on a set of sustainability indicators can be built. These models can rely on summary models developed at field and farm levels (e.g., the impact of hedges on neighbouring crop production, the probability of wildlife damage in relation to the surrounding landscape configuration). Models are then used to explore 'what-if' scenarios around changes in farm practices, collective arrangement that influence land use and land cover.

3. Typical outputs

A typical output of field-level analysis is a map of the performance of a given sustainable intensification options, its spatial variations - owing to climate and soil variations - and its temporal variations - owing to e.g. climate inter-annual variability or mid- and long-term changes in soil fertility. Figure 14A shows an example of contrasting areas in terms of average and variability of maize response to fertiliser in central Senegal [RA4].

At farm-level, a typical output would be the impact of a subsidy/payment for ecosystem service on the implementation of a given sustainable intensification option. Within-sites variations (according to farm type) and between sites variations are of particular interest. In the example (Figure 14B), the sustainable intensification option could be the implementation of residue mulching. Figure 14B clearly shows that in site 1, no farm would implement the option, regardless of the amount of the subsidy, indicating that constraints beyond cash are at stake. In site 2, some farms would implement the options while others would not, indicating that cash is the main limiting factor for some farm type but not for other. Site 3 is similar to Site 2, but overall the implementation of the option would be larger, possibly pointing to the fact that the option performs better (thanks to better climate and/or soil) in that site. This understanding of trade-offs and opportunities at the farm level can help guide investments for a wider implementation of sustainable intensification options.

At landscape level, a typical output would be a matrix that shows, for a set of scenarios, the relative change (compared to baseline) in the values of a set of sustainability indicators (Figure 14C). The scenarios correspond to changes in external factors (e.g. rainfall, economic situation with price of inputs and outputs), that translate into changes in land use and land cover maps. The local changes in land use and land cover in response to the external context can be co-design with local stakeholders. The baseline is the current land use and land cover. The indicators can be numerous and need to cover the dimension of food security, climate change adaptation and mitigation, biodiversity conservation, and locally-relevant indicators as pointed by stakeholders. This level of analysis helps to understand the landscape-level implications of the re-configurations analysed at farm level.

4. Interactions between field, farm, and landscape outcomes

The three levels of this framework interact. Outcomes at field-level are fed into the farm-level analysis, e.g., prediction of the average performance of intercropping for contrasting nutrient inputs (depending on farm type and site). In a similar fashion, farm-level output informs the landscape analysis: e.g., prediction of the aggregated changes in land use based on the way a subsidy impacts the implementation of a sustainable intensification option. Essential to this framework is the interaction with stakeholders, farmers, extension services, decision makers, development NGOs and private sector actors. These interactions are critical to align the worldviews of local stakeholders and researchers when addressing key research questions [PA30], and crucial to inform the definition of indicators that need to be assessed when looking at sustainability issues at field, farm and landscape levels [PA10]. Engagement with stakeholder help refine the performance indicators considered at the field level, define the scenarios of land use and land cover change at landscape level, ensuring feedback loops and co-learning between research and stakeholders [PA6].

In what follows I will show how I plan to make this framework ‘come to life’ with on-going and forthcoming projects that (will) support PhD and Postdoc students, and also point to some on-going and future analyses of my own and from colleagues in my research unit.

III. Expected results

1. How does spatial and temporal variation in climate and soils drives the agronomic and environmental performance of sustainable intensification options?

I plan to explore the spatio-temporal variations in the performance of a set of diversifications strategies and integrated soil fertility management.

Diversification strategies

Together with PhD student Mathilde de Freitas (Table 4), we aim at understanding how intercropping can both help intensify crop production and adapt to climate variability, at the scale of sub-Saharan Africa. Following the approach of Figure 13 and 14A, the study makes use of a bottom-up approach and relies on a network of on-station and on-farm experimentations in Mali, Senegal, Burkina Faso and Zimbabwe to calibrate and test the STICS model in its ability to accurately simulate competitions and complementarities for resource partitioning in intercropping. The detailed crop model can be synthesized in a summary model trained on the outputs of a sensitivity analysis of STICS, as pointed by the outcome of a Msc student that I co-supervised (Emma Sinibaldi, see part A). This summary model can in turn be used to extrapolate the benefits and constraints of intercropping at the scale of the continent, and offers the prospect to answer some of the key questions around scaling. Would cereal-

legume intercropping perform to the level it does on-station in the millions of ha of cropland in cereal-growing areas of sub-Saharan Africa? How would the land spared through better productivity aggregate over large scales, and would it be substantial enough to impact favourably biodiversity conservation and climate change mitigation? Because there are several other intercropping models, we are also involved in the execution and coordination of an AGMIP activity looking at how well various crop models can handle the simulation of intercropping. This effort will generate critical insights into how model assumptions and processes influence simulations accuracy, and also ultimately help expand the calibration database currently mobilized by Mathilde with two additional sites in a dry-cool (South Africa) and humid-warm (Ghana) calibration sites.

When we think about diversification of cropping system, sorghum is also a key candidate. Maize is currently number one in terms of calorie production on the African continent (OCDE and FAO, 2016). Maize outperforms sorghum in terms of average yield and response to nutrient inputs, thanks to greater selection efforts in that direction over the past decades (Parra et al., 2022). Sorghum, on the other hand, has better adaptation to drought conditions (van Oosterom et al., 2021) and local cultivars have greater sensitivity to photoperiod, which helps adapt to changes in growing season length (Kouressy et al., 2008). In many parts of Africa, farmers replace traditional sorghum with maize, while NGOs and governments increasingly support a return to 'small grains' as a meaningful strategy for food security and resilience to climate change (e.g. <https://www.bbc.com/news/world-africa-62166540>). Yet, there is to date no comprehensive study trying to determine for which agroecological regions, and for which crop management, maize or sorghum is a better option for increased and more stable yields in the face of climate change. Our recent advances in crop and climate modelling (see [PA25]), and already compiled large dataset for maize (see [PA12] and [PA21]) and opportunities to leverage the data collected by Cirad on sorghum over the past decades in contrasting sites, offer the prospect to answer that question. Together with a PhD student who will be recruited before the end of 2024 (Table 4), we will explore how agroecological regions, cultivar and crop management influence the comparative performance of maize and sorghum in terms of yield level and yield stability. Similar to the study on intercropping, we will rely on existing detailed sorghum experiments with detailed monitoring of crop growth in Mali, Senegal, Kenya and Zimbabwe, calibrate a set of crop models to explore what if scenarios in term of management, soil type, and climate.

Agroforestry – the mixing of trees and crops on the same plot - is also a relevant diversification strategy. How trees compete with crops for light, water and nutrients, and how this depends on tree species and location is rather well known (e.g., Ndoli et al., 2017). Of key interest is the interplay between i) an increase in soil organic matter – thanks to tree litter - and provision of key nutrients to the crop, and ii) competition for light and water between the crop and the tree. Crop models can help disentangle the two effects and understand whether tree presence ultimately leads to greater or smaller crop productivity ([PA28], Sida et al., 2018). Useful data looking at the impact of trees on crop in contrasting parklands of Senegal, Cameroun, Rwanda and Ethiopia has been generated by CIMMYT, CIRAD and their partners. Together with the advances in mapping parklands across the continent that are planned with the new Horizon-Galileo project, this could be used to provide i) realistic estimates of how current parkland improve (or constrain) crop growth, and ii) explore the impact of future parklands density and composition on aggregated crop production.

Integrated soil fertility management

Diversification alone will not deliver its full promises without integrated soil fertility management (ISFM). In the coming years, I will contribute to several efforts describing the regional contrasts in ISFM performance, with the ultimate goal of exploring how such option can be scaled throughout the continent.

I will be leading a first effort, as part of my involvement within the RAIZ project, to understand the risk related to the intensification of maize production with N mineral fertilizer. Similar to the case-study

for the groundnut basin in Senegal [RA4], we want to generate continent-wide aggregate of the area (size and location) where response to fertilizer is guaranteed (i.e., high mean response), but where inter-annual variability is so high that it requires de-risking mechanisms (e.g., irrigation or insurance). This piece of information is critical to inform the current development agenda around the use of fertilizer in SSA (https://au.int/sites/default/files/documents/44056-doc-AFSHS_Decl_4_II_Rev_2_E.pdf). Again, the study will rely on detailed maize experimentations throughout the continent, used to calibrate and validate an ensemble of crop models, that can then be used to perform spatial exploration of maize performance, for a series of historical and future climates.

The second effort will be led by a colleague at AIDA within the RAIZ project and aims at understanding how weather forecast can help inform the choice of varieties and nutrient input to better cope with climate inter-annual variability. I am collaborating closely with this colleague, and a proof-of-concept is undergoing at the five sites used for model calibration, but ultimately the analysis will be carried across all maize growing areas in SSA.

In collaboration with PhD student Asse Mbengue (Table 1), we also want to explore how augmenting the quality of rainfall geodata with dense network of observations, can help improve the prediction of regional millet yield in Senegal.

Of critical importance for the three above-mentioned studies, is how well current crop models simulate the mineralization of soil organic matter and nutrient provision to crops. A detailed testing of the robustness of the processes and parameters currently included in crop models needs to be carried-out. This must leverage observations of soil mineral nitrogen and plant nitrogen uptake across the contrasting soil types and climate of SSA. This study will be carried-out by a postdoc student who will start before the end of 2024 within the 'ALAMOD' project of the PEPR 'FairCarbon' (Table 4).

The above-mentioned studies rely on crop models that handle water and N stress only, and overlook the impact of soil meso and micro-nutrient. Deficiency of meso- and micro nutrient can cause non-responsiveness of soils to nutrient inputs (Kihara et al., 2016). Crop models that don't account for this process will completely overlook this issue. Comprehensive database of nutrition omission trials (NOTs) in several contrasting climates and soil across SSA exist (Njoroge et al., 2017) and can be leveraged to understand the factors driving non-responsiveness of soils. Possibly, a postdoc student within the 'Africa Union Soil Observatory' (AUSO) project led by ISRIC will explore this issue with the aim of mapping non-responsive soils across the continent (Table 4). A machine learning model will be trained on NOTs observations to understand threshold of nutrient concentration that drive low response, and will then be used to predict crop response to nutrient addition on large spatial scales.

A focus on environmental variables

Though I did pay some attention to environmental indicators in my previous research (e.g., nitrogen leaching in [PA17], nitrogen use efficiency in [RA10], C sequestration in [PA24] and [RA6]), I want to strengthen the analysis of this environmental dimension in my future work. Of considerable interest when dealing with climate change mitigation in cropping systems are N₂O emissions, and also geophysical effects like albedo (darker soil contributing more to warming the atmosphere than bright soils). Changes in N₂O emissions and albedo, for contrasting sustainable intensification options (crop residue mulching, intercropping) is currently being investigated in on-station experiment at the University of Zimbabwe in Harare. Together with two PhD students (supervised by AIDA colleague Rémi Cardinael), we will explore how well crop models can account for the impact of these sustainable intensification options on N₂O emissions and albedo (Table 4).

2. What are key trade-offs for resource allocation at farm level (cash, labour, land), and how does this vary locally (farm type) and more broadly across the continent (agroecological zones)?

The first axis of this research proposal will help assess the agronomic and environmental performance of a broad set of sustainable intensification options. It is very clear from the existing literature and some previous research work that one-size-fits all approaches do not work when looking at farm-level implementation.

Together with colleagues at AIDA-Cirad, we aim at understanding how the external economic context, and farm type, can impact the opportunity for smallholder farms to grow more legumes. Integration of legumes is here seen as a sustainable intensification option that offers the prospect to reduce the need for mineral fertilizer (hence delivering an important environmental benefit). We focus on three case-studies across sub-Saharan Africa (Senegal, Burkina Faso, Zimbabwe), with one additional site in southern Asia (Lao PDR). These sites are contrasting in terms of agroecological potential (low vs high rainfall), cash crop opportunities (maize, tobacco, cotton), distance to market, and input and output prices. This work builds on previous and on-going detailed household characterizations at the sites. A simple farm bio-economic model, as built by Lairez et al. (2023), will be used. Farmers' objectives and constraints (in terms of food self-sufficiency, cash and labour flows) are specified, and the model is then tested for its ability to match observed land allocation for contrasting farm types at the sites. The analysis of current observed land allocation has indicated that legume share seldom exceeds 25% of total cropland. The model will be used to explore how variations in the economic context – e.g., changes in output/input price ratio, payment for ecosystem services associated with the growing of more legumes – can help increase the share of legumes in cropland (see Figure 14B for an example of possible output). Nudging farmers to implement environmentally friendly practices is a hot topic (Ngoma et al., 2020). Understanding how context (climate, soils, current infrastructures) drive the amount of the subsidy or payment for ecosystem services, is of critical importance for decision makers. The analysis will help locate high-priority regions where this nudging effect is very small, and regions where it is high requiring further attention and analysis.

This study is a proof-of-concept of the approach, currently led by Juliette Lairez (AIDA), with help of a Msc student within the OneCG 'Agroecology Initiative' (Table 4). This axis of research is in close connection to the previous one: more sustainable intensification options need to be assessed (e.g., intercropping of legumes, agroforestry, crop residues mulching) and their environmental benefits carefully weighted. More case-study sites with detailed household surveys should be added to extend the representativity and validity of the study. Surely this could form the basis of a PhD study. Recent discussion between Cirad and UE- Directorate-General for International Partnerships (DG INTPA) could lead to a new project that will assess the scope for agroecological transition at country level, for contrasting nations of SSA – and include farm-level analysis with bio-economic models (Table 4).

This effort aligns with a collaboration with a team of economists (Damien Jourdain and PhD student Amandine Belard at Cirad – Umr GECO) that I have been able to initiate within the RAIZ project. Farm bioeconomic modelling relies on this assumption that farmers would make rational choices, i.e. they try to maximize their revenue under a set of constraints, with perfect knowledge of the profitability and labour demand of different crop and livestock activities. Of course, this does not hold true in the real world. Discrete choice experiments (DCE) can help to assess the influence of other factors (e.g. partial knowledge of the performance of practices, gender preferences, values and beliefs, risk aversion) on farmers' decision making [RA2], but these remain virtual experiments. Eventually, one

wants to test farmers decision in the real world, using randomized control trials (RCTs) where farmers have to implement the improved practise if they accept a given level of incentive (e.g. Duflo et al., 2009). These three methods, farm bioeconomic modelling, DCE, and RCTs, are complementary. Farm bioeconomic modelling can be performed by agronomists (in close collaboration with economists). DCE and RCTs are led by economists, with input from agronomists. I have good hope that the collaboration with economists initiated within the RAIZ project can be pursued in the future, possibly with a new call to be issued by the EU delegation in Zimbabwe on Climate Smart Agriculture.

I have often been challenged that the broad external socio-economic context cannot be changed, and that we, systems agronomists and farm designers, need to take it for granted and co-design within fixed external socio-economic boundaries. I tend to disagree, as this external context (infrastructure, education, governmental support to agriculture) is rather unfavourable at the moment in many parts of sub-Saharan Africa, and strongly constrains what is achievable in terms of sustainable intensification and improvement of people's livelihood. The type of ex-ante analysis described here will certainly help make a stronger case for the need for strong public support to the agricultural sector and economic incentives for farmers if success stories have to happen.

3. Which landscape composition and configuration help reconcile food security, climate change mitigation and biodiversity conservation?

Together with PhD student Adrien Coquereau (Table 4), we are exploring how contrasted landscapes in terms of land use and land cover, and landscape composition and configuration, perform along a set of indicators related to food security, climate change mitigation and biodiversity conservation. The case study area is located in sub-humid Zimbabwe. Possible future landscapes are co-designed together with farmers, in response to a set of pre-identified external drivers (climate and external economic context). Adrien has been building an ad-hoc landscape model that computes the value of the indicators as a function of land use and land cover. For example, the size of the grazing land determines the maximum carrying capacity for livestock, that in turn sets the amount of manure available for application on cereal (maize). Manure availability and the size of the cropland sets the input rates, and predetermined crop nutrient response functions (building on the field-level modelling of [RA9]) are used to determine yield and cereal production for the entire cropland. Landscape-level food self-sufficiency is computed as the ratio of food produced over the needs of the local population (that depends on the scenarios that also include contrasting population growth and migration). Literature values for woodland productivity and regeneration are used to compute firewood availability. Weighted against the need of rural population, this sets the landscape self-sufficiency in firewood, an indicator of a key indirect link between landscape and food security. Soil carbon stocks, and their change between scenarios, are computed from the area of the different land uses and their respective stocks (estimated based on field measurements of [RA6]). Biodiversity is assessed through the functional integrity index that encompasses the combination of habitat quantity, quality, and spatial configuration (Mohamed et al., 2024). The work of Adrien is a typical example of how field and landscape analyses can complement each other, in line with the proposed framework of Figure 13.

These ad-hoc models are then used to compute the matrix presented in Figure 14C. The matrix helps understand how a given scenario impacts indicators of sustainability. Identifying the indicator(s) that receive a low value, whatever the scenario, helps identify local sustainability problems, whatever the (unknown) changes in the external context. For example, in the case of the Murehwa district in sub-humid Zimbabwe, wood cover would decrease in any of the scenarios: farmers indicated that with a favorable economy and climate they would expand tobacco production - at the expanse of woodland - in order to maximize their income. In the case of an unfavorable economy and climate, they would

expand cereal cultivation – again at the expense of woodland. This sets the basis for the identification of ‘no regret’ strategies, e.g., collective actions like exclosures, that can be undertaken now, and that will yield benefits in the future, whatever the uncertainty in the external context.

The work of Adrien currently involves only one case-study site. Cross-site comparisons will help identify i) what are key sustainability issues (poor performance along a given indicator, whatever the external context) and ii) what are the required collective actions. Some strategies may be relevant across all sites (i.e., very robust), while other may work only in some of the sites; such findings are critical for priority setting around which type of intervention(s) to favour at the regional level.

There is an opportunity to expand the approach carried-out by Adrien to another site in semi-arid Zimbabwe, close to the Mana-Pools national park – where human conflicts are a key issue - within the frame of the new OneCGIAR Science Program 2 on ‘Multifunctional Landscapes’ (Table 4).

Table 4: Projects and students to support the research project. Supervised students are underlined.

Scientific objective	Theme	Who leads?	Project (duration)	Key research questions
1) Understanding spatial and temporal variation in the agronomic and environmental performance of sustainable intensification options	Diversification with legumes (intercropping)	<u>PhD student M. de Freitas</u>	IntercropValues (2022-2026)	How accurate is the STICS model in simulating competitions in intercropping under contrasted tropical conditions? Can cereal-cowpea intercropping help stabilize yield? Can cereal-cowpea intercropping help improve nitrogen use efficiency?
	Diversification with legumes (intercropping)	PhD student Adam Adam	Desira LEG4DEV (2020-2025) - Agmip	How does the structure of current intercropping models impact model accuracy?
	Diversification with sorghum	<u>PhD student Artur Madal</u>	PEPR TRACCS (2023-2030)	How does soil and climate impact the comparative performance of maize and sorghum?
	Risk of intensification of maize-based systems	Myself	Desira RAIZ (2022-2025)	How does soil and climate impact the risk of maize intensification with more mineral fertiliser?
	Benefits of climate services and weather forecast	AIDA Colleague Guillaume Bruelle	Desira RAIZ (2022-2025)	How can weather forecast help optimise crop management for sustainable intensification of maize production?
	Soil organic matter mineralisation and impact of soil type	Postdoc student to be determined	PEPR FairCarbon (2023-2030)	Can current crop models accurately simulate N provision by soils in the tropics?
	Non-responsive soils	Postdoc student to be determined	Horizon AUSO (2025-2028)	What are key soil properties and threshold values that explain soil non-responsiveness to fertiliser? Where are non-responsive soils across sub-Saharan Africa and what is their aggregated area?
	Influence of the quality of rainfall geodata on model predictions	PhD student Asse Mbenge	-	How does the quality of geospatial rainfall data influence crop model simulation of millet response to fertiliser in Senegal?
	GHG emissions and N2O	PhD student Hope Mazungunye PhD student Anderrahim Bouhenache	IntercropValues (2022-2026) Desira RAIZ (2022-2025)	What is the impact of extreme rainfall on maize-cowpea intercropping performance and GHG emissions? What is the impact of extreme rainfall on soil organic matter mineralisation and maize-based systems performance?
2) Key trade-offs for resource allocation at farm level that impede the large-scale implementation of sustainable intensification options	Subsidy for the integration of legumes in farming systems	AIDA Colleague Juliette LAIREZ	One CG Agroecology Initiative (2021-2024)	How does climate and socio-economic conditions impact the level of subsidy required to trigger large scale integration of legumes into farming systems?
	Broad assessment of incentives required for the integration of sustainable intensification options in African farming systems	Postdoc to be determined	DG INTPA	How does climate and socio-economic conditions impact the type of incentive required to trigger large scale integration of sustainable intensification options into farming systems?

3) Landscape composition and configuration that help reconcile food security, climate change mitigation and biodiversity conservation	Impact of agroecological landscape on food security and participatory foresight	<u>PhD student Adrien Coquereau</u>	Desira RAIZ (2022-2025)	Do landscapes that comply with agroecological principle improve food security?
	Human-wildlife conflicts	Own analysis, PhD student Telma Sibanda	OneCG MP2	Can participatory foresight help with building future-proof landscapes? What are the landscape compositions and configurations that offer the best compromise for rural livelihoods and biodiversity, maximizing the delivery of ecosystem services while minimizing disservices?

REFERENCES

- Affholder, F., 1997. Empirically modelling the interaction between intensification and climatic risk in semiarid regions. *Field Crops Research* 52, 79–93. [https://doi.org/10.1016/S0378-4290\(96\)03453-3](https://doi.org/10.1016/S0378-4290(96)03453-3)
- Affholder, F., Tittonell, P., Corbeels, M., Roux, S., Motisi, N., Tixier, P., Wery, J., 2012. Ad hoc modeling in agronomy: what have we learned in the last 15 years? *Agronomy Journal* 104, 735–748. <https://doi.org/10.2134/agronj2011.0376>
- Beal, T., Massiot, E., Arsenault, J.E., Smith, M.R., Hijmans, R.J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLOS ONE* 12, e0175554. <https://doi.org/10.1371/journal.pone.0175554>
- Bedoussac, L., Justes, E., 2010. The efficiency of a durum wheat-winter pea intercrop to improve yield and wheat grain protein concentration depends on N availability during early growth. *Plant and Soil* 330, 19–35. <https://doi.org/10.1007/s11104-009-0082-2>
- Berzaghi, F., Cosimano, T., Fullenkamp, C., Scanlon, J., Fon, T.E., Robson, M.T., Forbang, J.L., Chami, R., 2022. Value wild animals' carbon services to fill the biodiversity financing gap. *Nat. Clim. Chang.* 12, 598–601. <https://doi.org/10.1038/s41558-022-01407-4>
- Bonilla Cedrez, C., Chamberlin, J., Hijmans, R.J., 2021. Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nat Food* 2, 766–772. <https://doi.org/10.1038/s43016-021-00370-1>
- Cardinael, R., Guibert, H., Kouassi Brédoumy, S.T., Gigou, J., N'Goran, K.E., Corbeels, M., 2022. Sustaining maize yields and soil carbon following land clearing in the forest–savannah transition zone of West Africa: Results from a 20-year experiment. *Field Crops Research* 275, 108335. <https://doi.org/10.1016/j.fcr.2021.108335>
- Duflo, E., Kremer, M., Robinson, J., 2009. Nudging Farmers to Use Fertilizer: Theory and Experimental Evidence from Kenya (Working Paper No. 15131). National Bureau of Economic Research. <https://doi.org/10.3386/w15131>
- Faye, B., Webber, H., Naab, J.B., MacCarthy, D.S., Adam, M., Ewert, F., Lamers, J.P.A., Schleussner, C.-F., Ruane, A., Gessner, U., Hoogenboom, G., Boote, K., Shelia, V., Saeed, F., Wisser, D., Hadir, S., Laux, P., Gaiser, T., 2018. Impacts of 1.5 versus 2.0 °C on cereal yields in the West African Sudan Savanna. *Environmental Research Letters* 13, 034014. <https://doi.org/10.1088/1748-9326/aaab40>
- Franke, J., Müller, C., Elliott, J., Ruane, A.C., Jagermeyr, J., Balkovic, J., Ciais, P., Dury, M., Falloon, P., Folberth, C., Francois, L., Hank, T., Hoffmann, M., Izaurrealde, R.C., Jacquemin, I., Jones, C., Khabarov, N., Koch, M., Li, M., Liu, W., Olin, S., Phillips, M., Pugh, T.A.M., Reddy, A., Wang, X., Williams, K., Zabel, F., Moyer, E., 2019. The GGCM Phase II experiment: global gridded crop model simulations under uniform changes in CO₂, temperature, water, and nitrogen levels (protocol version 1.0). *Geoscientific Model Development Discussions* 1–30. <https://doi.org/10.5194/gmd-2019-237>
- Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., Rigolot, C., Ritzema, R.S., Rodriguez, D., van Asten, P.J.A., van Wijk, M.T., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences of the United States of America* 113, 458–463. <https://doi.org/10.1073/pnas.1518384112>
- Gérard, F., Affholder, F., Mane, N.F., Sall, M., 2020. Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal, in: Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal, *Papiers de recherche*. Agence

- française de développement, Paris Cedex 12, pp. 1–76.
<https://doi.org/10.3917/afd.gerar.2020.01.0001>
- Giller, K.E., Delaune, T., Silva, J.V., van Wijk, M., Hammond, J., Descheemaeker, K., van de Ven, G., Schut, A.G.T., Taulya, G., Chikowo, R., Andersson, J.A., 2021. Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options? *Food Sec.* <https://doi.org/10.1007/s12571-021-01209-0>
- Giller, K.E., Tittonell, P., Rufino, M.C., van Wijk, M.T., Zingore, S., Mapfumo, P., Adjei-Nsiah, S., Herrero, M., Chikowo, R., Corbeels, M., Rowe, E.C., Baijukya, F., Mwijage, A., Smith, J., Yeboah, E., van der Burg, W.J., Sanogo, O.M., Misiko, M., de Ridder, N., Karanja, S., Kaizzi, C., K'ungu, J., Mwale, M., Nwaga, D., Pacini, C., Vanlauwe, B., 2011. Communicating complexity: Integrated assessment of trade-offs concerning soil fertility management within African farming systems to support innovation and development. *Agricultural Systems* 104, 191–203. <https://doi.org/10.1016/j.agsy.2010.07.002>
- Grassini, P., Pittelkow, C.M., Cassman, K.G., Yang, H.S., Archontoulis, S., Licht, M., Lamkey, K.R., Ciampitti, I.A., Coulter, J.A., Brouder, S.M., Volenec, J.J., Guindin-Garcia, N., 2017. Robust spatial frameworks for leveraging research on sustainable crop intensification. *Global Food Security, Food Security Governance in Latin America* 14, 18–22. <https://doi.org/10.1016/j.gfs.2017.01.002>
- Hammond, J., Fraval, S., van Etten, J., Suchini, J.G., Mercado, L., Pagella, T., Frelat, R., Lannerstad, M., Douchamps, S., Teufel, N., Valbuena, D., van Wijk, M.T., 2017. The Rural Household Multi-Indicator Survey (RHoMIS) for rapid characterisation of households to inform climate smart agriculture interventions: Description and applications in East Africa and Central America. *Agricultural Systems* 151, 225–233. <https://doi.org/10.1016/j.agsy.2016.05.003>
- Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B.M., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., Kwabena, N.A., 2017. Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. *Nutr Cycl Agroecosyst* 109, 77–102. <https://doi.org/10.1007/s10705-017-9870-x>
- IPCC, 2021. Climate Change 2021: The Physical Science Basis | Climate Change 2021: The Physical Science Basis.
- Jägermeyr, J., Müller, C., Ruane, A.C., Elliott, J., Balkovic, J., Castillo, O., Faye, B., Foster, I., Folberth, C., Franke, J.A., Fuchs, K., Guarin, J.R., Heinke, J., Hoogenboom, G., Iizumi, T., Jain, A.K., Kelly, D., Khabarov, N., Lange, S., Lin, T.-S., Liu, W., Mialyk, O., Minoli, S., Moyer, E.J., Okada, M., Phillips, M., Porter, C., Rabin, S.S., Scheer, C., Schneider, J.M., Schyns, J.F., Skalsky, R., Smerald, A., Stella, T., Stephens, H., Webber, H., Zabel, F., Rosenzweig, C., 2021. Climate impacts on global agriculture emerge earlier in new generation of climate and crop models. *Nat Food* 2, 873–885. <https://doi.org/10.1038/s43016-021-00400-y>
- Jayne, T.S., Chamberlin, J., Benfica, R., 2018. Africa's Unfolding Economic Transformation. *The Journal of Development Studies* 54, 777–787. <https://doi.org/10.1080/00220388.2018.1430774>
- Kebede, Y., Baudron, F., Bianchi, F., Tittonell, P., 2018. Unpacking the push-pull system: Assessing the contribution of companion crops along a gradient of landscape complexity. *Agriculture, Ecosystems & Environment* 268, 115–123. <https://doi.org/10.1016/j.agee.2018.09.012>
- Kihara, J., Nziguheba, G., Zingore, S., Coulibaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 229, 1–12. <https://doi.org/10.1016/j.agee.2016.05.012>
- Kilic, T., Winters, P., Carletto, C., 2015. Gender and agriculture in sub-Saharan Africa: introduction to the special issue. *Agricultural Economics* 46, 281–284. <https://doi.org/10.1111/agec.12165>
- Kouressy, M., Dingkuhn, M., Vaksman, M., Heinemann, A.B., 2008. Adaptation to diverse semi-arid environments of sorghum genotypes having different plant type and sensitivity to

- photoperiod. *Agricultural and Forest Meteorology* 148, 357–371.
<https://doi.org/10.1016/j.agrformet.2007.09.009>
- Lairez, J., Jourdain, D., Lopez-Ridaura, S., Syfongxay, C., Affholder, F., 2023. Multicriteria assessment of alternative cropping systems at farm level. A case with maize on family farms of South East Asia. *Agricultural Systems* 212, 103777. <https://doi.org/10.1016/j.agry.2023.103777>
- Launay, C., Constantin, J., Chlebowski, F., Houot, S., Graux, A.-I., Klumpp, K., Martin, R., Mary, B., Pellerin, S., Therond, O., 2021. Estimating the carbon storage potential and greenhouse gas emissions of French arable cropland using high-resolution modeling. *Global Change Biology* 27, 1645–1661. <https://doi.org/10.1111/gcb.15512>
- Masters, W.A., Rosenblum, N.Z., Alemu, R.G., 2018. Agricultural Transformation, Nutrition Transition and Food Policy in Africa: Preston Curves Reveal New Stylised Facts. *The Journal of Development Studies* 54, 788–802. <https://doi.org/10.1080/00220388.2018.1430768>
- Mohamed, A., DeClerck, F., Verburg, P.H., Obura, D., Abrams, J.F., Zafra-Calvo, N., Rocha, J., Estrada-Carmona, N., Fremier, A., Jones, S.K., Meier, I.C., Stewart-Koster, B., 2024. Securing Nature's Contributions to People requires at least 20%–25% (semi-)natural habitat in human-modified landscapes. *One Earth* 7, 59–71. <https://doi.org/10.1016/j.oneear.2023.12.008>
- Ndoli, A., Baudron, F., Schut, A.G.T., Mukuralinda, A., Giller, K.E., 2017. Disentangling the positive and negative effects of trees on maize performance in smallholdings of Northern Rwanda. *Field Crops Research* 213, 1–11. <https://doi.org/10.1016/j.fcr.2017.07.020>
- Ngoma, H., Hailu, A.T., Kabwe, S., Angelsen, A., 2020. Pay, talk or 'whip' to conserve forests: Framed field experiments in Zambia. *World Development* 128, 104846.
<https://doi.org/10.1016/j.worlddev.2019.104846>
- Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. *Field Crops Research* 214, 321–330. <https://doi.org/10.1016/j.fcr.2017.09.026>
- OCDE, FAO, 2016. Agriculture in Sub-Saharan Africa: Prospects and challenges for the next decade, in: *OECD-FAO Agricultural Outlook 2016-2025*. Paris.
- Ojiem, J.O., Franke, A.C., Vanlauwe, B., de Ridder, N., Giller, K.E., 2014. Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *Field Crops Research* 168, 75–85. <https://doi.org/10.1016/j.fcr.2014.08.004>
- Parra, G., Borrás, L., Gambin, B.L., 2022. Crop attributes explaining current grain yield dominance of maize over sorghum. *Field Crops Research* 275, 108346.
<https://doi.org/10.1016/j.fcr.2021.108346>
- Paul, B.K., Frelat, R., Birnholz, C., Ebong, C., Gahigi, A., Groot, J.C.J., Herrero, M., Kagabo, D.M., Notenbaert, A., Vanlauwe, B., van Wijk, M.T., 2017. Agricultural intensification scenarios, household food availability and greenhouse gas emissions in Rwanda: Ex-ante impacts and trade-offs. *Agricultural Systems*. <https://doi.org/10.1016/j.agry.2017.02.007>
- Pender, J., Jagger, P., Nkonya, E., Sserunkuuma, D., 2004. Development Pathways and Land Management in Uganda. *World Development* 32, 767–792.
<https://doi.org/10.1016/j.worlddev.2003.11.003>
- Rattalino Edreira, J.I., Andrade, J.F., Cassman, K.G., van Ittersum, M.K., van Loon, M.P., Grassini, P., 2021. Spatial frameworks for robust estimation of yield gaps. *Nat Food* 2, 773–779.
<https://doi.org/10.1038/s43016-021-00365-y>
- Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., Sall, M., 2017. Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. *Agricultural Systems* 156, 149–176.
<https://doi.org/10.1016/j.agry.2017.05.015>
- Ripoche, A., Autfray, P., Rabary, B., Randriamanantsoa, R., Blanchart, E., Trap, J., Sauvadet, M., Becquer, T., Letourmy, P., 2021. Increasing plant diversity promotes ecosystem functions in rainfed rice based short rotations in Malagasy highlands. *Agriculture, Ecosystems & Environment* 320, 107576. <https://doi.org/10.1016/j.agee.2021.107576>

- Ritzema, R.S., Frelat, R., Douxchamps, S., Silvestri, S., Rufino, M.C., Herrero, M., Giller, K.E., López-Ridaura, S., Teufel, N., Paul, B.K., Wijk, M.T. van, 2017. Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. *Food Sec.* 9, 115–131. <https://doi.org/10.1007/s12571-016-0638-y>
- Rufino, M.C., Dury, J., Tittonell, P., van Wijk, M.T., Herrero, M., Zingore, S., Mapfumo, P., Giller, K.E., 2011. Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems* 104, 175–190. <https://doi.org/10.1016/j.agsy.2010.06.001>
- Sida, T.S., Baudron, F., Kim, H., Giller, K.E., 2018. Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agricultural and Forest Meteorology* 248, 339–347. <https://doi.org/10.1016/j.agrformet.2017.10.013>
- Sow, A., Seye, D., Faye, E., Benoit, L., Galan, M., Haran, J., Brévault, T., 2020. Birds and bats contribute to natural regulation of the millet head miner in tree-crop agroforestry systems. *Crop Protection* 132, 105127. <https://doi.org/10.1016/j.cropro.2020.105127>
- Udo, H.M.J., Aklilu, H.A., Phong, L.T., Bosma, R.H., Budisatria, I.G.S., Patil, B.R., Samdup, T., Bebe, B.O., 2011. Impact of intensification of different types of livestock production in smallholder crop-livestock systems. *Livestock Science* 139, 22–29. <https://doi.org/10.1016/j.livsci.2011.03.020>
- van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Tittonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—A review. *Field Crops Research* 143, 4–17. <https://doi.org/10.1016/j.fcr.2012.09.009>
- van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? *Proc Natl Acad Sci U S A* 113, 14964–14969. <https://doi.org/10.1073/pnas.1610359113>
- van Oosterom, E.J., Kulathunga, M.R.D.L., Deifel, K.S., McLean, G.B., Barrasso, C., Wu, A., Messina, C., Hammer, G.L., 2021. Dissecting and modelling the comparative adaptation to water limitation of sorghum and maize: role of transpiration efficiency, transpiration rate and height. in *silico Plants* 3, diaa012. <https://doi.org/10.1093/insilicoplants/diaa012>
- Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *SOIL* 1, 491–508. <https://doi.org/10.5194/soil-1-491-2015>
- Waddington, S.R., Mekuria, M., Siziba, S., Karigwindi, J., 2007. Long-term yield sustainability and financial returns from grain legume–maize intercrops on a sandy soil in subhumid north central zimbabwe. *Experimental Agriculture* 43, 489–503. <https://doi.org/10.1017/S0014479707005303>
- Wichern, J., Heerwaarden, J. van, Bruin, S. de, Descheemaeker, K., Asten, P.J.A. van, Giller, K.E., Wijk, M.T. van, 2018. Using household survey data to identify large-scale food security patterns across Uganda. *PLOS ONE* 13, e0208714. <https://doi.org/10.1371/journal.pone.0208714>

SUMMARY (IN FRENCH)

Ce mémoire vise à présenter ma contribution à la compréhension de la manière dont l'intensification durable de la production agricole peut aider à réduire l'insécurité alimentaire, tout en s'adaptant au changement climatique, voire en l'atténuant, dans le contexte de l'Afrique sub-Saharienne.

A) Présentation du candidat

Né en 1986 dans les alpes françaises, j'ai déménagé en Côte d'Ivoire à l'âge de six ans où j'ai fréquenté l'école française jusqu'à l'âge de douze ans. De retour en France en 1998, j'ai réalisé mes études de lycée et de classe préparatoire, puis poursuivi par des études d'agronomie à l'Ecole Nationale Supérieure d'Agronomie de Toulouse (ENSAT). Pendant cette période, j'ai pu acquérir une expérience de terrain au Mali lors d'un stage au CIRAD. Après une spécialisation en agronomie tropicale et deux stages au Mali avec l'ICRISAT, j'ai rejoint l'INRA en 2011 pour étudier la gestion des adventices dans les rizières de Camargue. Mon travail a donné lieu à un chapitre d'ouvrage auquel j'ai pu contribuer. J'ai ensuite travaillé comme expert junior à l'ICRISAT au Mali tout en poursuivant un doctorat à l'Université de Wageningen (2012-2015) sous la direction du professeur Ken Giller. Ma recherche de doctorat s'est concentrée sur les systèmes agricoles innovants dans le sud du Mali, impliquant l'expérimentation chez les agriculteurs, la modélisation des cultures et des systèmes d'exploitation, et la collaboration avec des chercheurs locaux. J'ai défendu ma thèse de doctorat avec quatre chapitres publiés. Pendant mon doctorat, j'ai pu superviser des techniciens de terrain et j'ai construit mon réseau scientifique international. Mes séjours antérieurs au Mali et ma capacité à parler le bambara ont grandement facilité le travail participatif que j'ai effectué au cours de ma recherche doctorale. Après avoir terminé mon doctorat, j'ai travaillé comme postdoc à l'INRAE (2016-2018), en me concentrant sur les légumineuses et la modélisation des cultures, et j'ai pu publier deux articles.

En 2018, j'ai rejoint l'unité de recherche 'AIDA' au CIRAD à Montpellier pour étudier les impacts du changement climatique sur la sécurité alimentaire en Afrique subsaharienne. Pendant trois ans (2018-2021), j'ai pu coordonner un effort de modélisation dans le cadre du projet AGMIP, impliquant 25 groupes de modélisation. Cet effort a abouti à une publication clé sur l'impact du changement climatique sur les systèmes de culture à bas intrants des agricultures familiales d'Afrique sub-Saharienne. Au cours de cette période, j'ai également contribué au projet ARISE et développé un cadre d'analyse reliant les modèles de culture et les modèles hydrologiques, ceci ayant donné lieu à une publication. En outre, j'ai organisé un atelier international sur les engrais minéraux, qui a donné lieu à la publication d'un article sur leur importance pour la sécurité alimentaire pour deux pays d'Afrique de l'Est, l'Ouganda et la Tanzanie. J'ai collaboré avec des collègues chercheurs au sein de mon unité de recherche, ce qui a donné lieu à cinq autres publications, et j'ai supervisé activement deux étudiants en doctorat et trois étudiants en master, contribuant ainsi à quatre autres articles publiés. En 2021, j'ai participé à la rédaction du projet « Promouvoir l'intensification agroécologique pour le renforcement de la résilience » (RAIZ) en réponse à l'appel « Desira » de la Commission européenne. Ce projet a soutenu mon expatriation au Zimbabwe en 2022.

Dans le cadre du projet RAIZ, j'ai élaboré une proposition de doctorat à l'université de Wageningen et j'ai pu superviser un doctorant dont le travail a donné lieu à un article publié et trois autres en préparation. Je supervise également deux étudiants en doctorat à l'université du Zimbabwe, un étudiant ayant déjà publié un article. Je participe également à la supervision de deux étudiants Master à l'université du Zimbabwe. Au sein de RAIZ, je coordonne i) les activités du groupe de travail sur l'évaluation de la durabilité des systèmes agricoles à différentes échelles, et ii) l'implémentation des

essais agronomique sur le terrain par les doctorants, les techniciens et les agents de vulgarisation. Depuis janvier 2022, je suis détaché à temps partiel au CIMMYT pour renforcer les collaborations entre le CIRAD et le CIMMYT dans le cadre de l'initiative OneCG « Transformational Agroecology across food, land and water systems » (AE-I). En outre, je coordonne, avec des collègues de mon unité de recherche et du Cirad, le groupe AGMIP 'low-input' sur la modélisation de la dynamique du carbone à long terme. Ce travail a donné lieu à une publication et deux autres sont en préparation. J'ai pu maintenir des liens avec l'université de Wageningen en supervisant un doctorant et un postdoc. Récemment, j'ai dirigé la rédaction d'un article de perspective sur les engrais minéraux en Afrique, qui a été publié l'année dernière. Cet article met en lumière les limites du principe agroécologique de réduction des intrants en ce qui concerne les engrais minéraux en Afrique subsaharienne. J'ai été invité à présenter cet article en 2024, lors du Salon International de l'Agriculture à Paris, et lors du sommet de l'Union Africaine sur la santé des sols et les engrais minéraux qui s'est tenu à Nairobi.

B) Synthèse des activités de recherche antérieures

La sécurité alimentaire en Afrique subsaharienne s'est améliorée au cours des dernières décennies grâce à l'augmentation du PIB de nombreux pays, ce qui a eu un impact positif sur la santé et la nutrition. Toutefois, l'insécurité alimentaire reste un défi de taille, puisque plus d'un tiers des ménages ne parviennent pas à satisfaire leurs besoins alimentaires. Ce problème présente de multiples facettes, notamment liés à la disponibilité, l'accès, l'utilisation et la stabilité de l'alimentation. Cependant, la population du continent devrait doubler d'ici à 2050. L'augmentation de la production et de la disponibilité des denrées alimentaires reste donc essentielle. Le changement climatique, en particulier la fréquence accrue des phénomènes météorologiques extrêmes, menace les rendements agricoles et pourrait exacerber cette insécurité alimentaire.

L'intensification durable de la production agricole en utilisant les terres cultivées actuelles, offre la possibilité de contribuer à l'amélioration de la disponibilité alimentaire et à la réduction de l'insécurité alimentaire, tout en s'adaptant au changement climatique, voire en l'atténuant. Les options pour une intensification durable comprennent la gestion intégrée de la fertilité des sols (GIFS, c'est à dire l'utilisation de variétés améliorées en combinaison avec des apports d'engrais minéraux et organiques) et la diversification avec des légumineuses (par le biais de rotations ou de cultures associées).

Cadre général de la recherche

Au cours des quinze dernières années, j'ai étudié le potentiel de l'intensification durable pour faire face à l'insécurité alimentaire et à l'adaptation au changement climatique en Afrique subsaharienne. Mon travail s'est concentré sur trois lacunes majeures en matière de connaissances :

- i) Comment les options d'intensification durable peuvent-elles être adaptées aux contextes de la petite agriculture familiale ?
- ii) Dans quelles conditions (où, pour quel type d'agriculteur) ces options peuvent-elles être extrapolées au niveau régional ?
- iii) Quels sont les co-bénéfices de ces options en termes d'adaptation et d'atténuation du changement climatique ?

Mes recherches s'articulent autour de quatre thèmes principaux. Le premier thème, « Comprendre les processus expliquant les avantages observés des options d'intensification durable », met l'accent sur la manière dont les processus naturels tels que la fixation biologique de l'azote et la santé des sols peuvent aider à surmonter les limitations en eau et en nutriments, ainsi qu'à atténuer les pressions exercées par les ravageurs et les maladies.

Le deuxième thème, « Comprendre la variabilité interannuelle des performances des options d'intensification durable et les possibilités d'atténuer les risques », s'appuie sur des modèles sol-culture utilisés pour analyser les interactions complexes entre les pratiques agricoles, le sol et le climat. L'objectif est d'extrapoler les résultats des expériences sur le terrain à des échelles spatiales et temporelles plus larges.

Le troisième thème porte sur l'intégration des contraintes et des opportunités au niveau de l'exploitation dans l'analyse de la transition des systèmes vers une intensification durable. Reconnaissant l'hétérogénéité des exploitations agricoles, ce thème examine comment les caractéristiques individuelles des exploitations agricoles - telles que la disponibilité des ressources, leurs objectifs et leurs contraintes - affectent l'efficacité des options d'intensification durable, soulignant la nécessité d'approches personnalisées.

Le quatrième thème est « Évaluer les possibilités d'extrapolation des résultats locaux au niveau régional/pays ». Ce thème utilise la théorie des « domaines de recommandation » pour explorer le potentiel d'extrapolation des options d'intensification durable identifiées. Il vise à utiliser les outils récents de modélisation mécaniste (sol-culture) et statistique, en combinaison avec des données géospatiales, afin d'identifier les zones où les agriculteurs se trouvent dans des conditions similaires.

Thème 1 : Comprendre les processus expliquant les avantages observés des options d'intensification durable

Les associations céréales-légumineuses sont un point d'entrée essentiel pour la diversification des systèmes de culture. J'ai étudié les performances de ce type d'association de culture dans les régions semi-arides du sud du Mali et du centre du Sénégal – au travers des exemples des associations mil-niébé et de sorgho-niébé, en utilisant des expérimentations factorielles répétées en station. En collaboration avec des étudiants en doctorat, nous avons constaté qu'avec des dispositifs additifs (c'est-à-dire la même densité de céréales en association et en culture pure), la légumineuse entraînait peu ou pas du tout en compétition avec la céréale. Très souvent, les 'Land Equivalent Ratio' (LER) étaient supérieurs à 1, ce qui indique un avantage de la culture associée par rapport à la culture pure en termes de productivité de la terre, et ce, grâce aux complémentarités dans l'utilisation de l'eau et des nutriments entre les deux cultures. Nous avons observé une diminution des avantages de la culture associée avec la fertilisation en azote minéral au Mali, conformément aux résultats obtenus dans les systèmes de culture tempérés des pays industrialisés. Les expérimentations de culture associée dans les champs des agriculteurs, que j'ai effectués pendant mon doctorat dans le sud du Mali, ont donné des résultats complètement différents. Bien que certains champs aient affiché un comportement similaire à celui trouvé en station, de nombreux champs présentaient des LER inférieurs à un (indiquant moins de terre nécessaire en culture pure pour produire le même rendement qu'en culture associée). Ces résultats illustrent le fait que le contexte de l'agriculteur peut fortement influencer la performance d'une option donnée. Dans le même ordre d'idées, la réponse des céréales aux engrais a été très variable d'un champ à l'autre. Ces interactions entre la performance des options pour l'intensification durable et les circonstances des agriculteurs appellent à l'identification de combinaisons option x contexte. J'ai participé à la conceptualisation de ces « niches socio-écologiques » dans un article publié pendant mon doctorat, et j'ai appliqué le concept à mon cas d'étude dans le sud du Mali. L'analyse des données d'essai que j'ai collectées au cours de mon étude de doctorat (372 essais sur quatre ans sur une gamme d'options de gestion intégrée de la fertilité et de diversification à l'aide de légumineuses) a démontré l'influence déterminante de la culture précédente et du type de sol sur les performances

des options. Les agriculteurs appliquent principalement des engrais minéraux sur le coton (leur culture de rente). Par conséquent, lorsque le coton était la culture précédente, les sols étaient généralement riches en nutriments et les cultures associées se comportaient d'une manière très similaire à celle observée dans les expérimentations en station (c'est-à-dire une concurrence limitée entre la légumineuse et la céréale, avec un LER généralement supérieur à un). Au contraire, lorsque le sorgho ou le mil était la culture précédente (moins d'applications d'engrais), les sols étaient moins fertiles et la légumineuse était généralement plus performante que la céréale. Cette compréhension a permis d'identifier, avec les agriculteurs, des « niches » pour la mise en œuvre de ces options, c'est-à-dire des combinaisons de type de sol et de culture précédente où les avantages agronomiques et la rentabilité des options étaient maximisés.

Thème 2 : Comprendre la variabilité interannuelle des performances des options d'intensification durable et les possibilités d'atténuer les risques climatiques

Les études à long terme sur l'intensification durable en Afrique sub-Saharienne sont rares. Les modèles de culture sont des outils utiles pour explorer la variabilité interannuelle des performances d'un ensemble de pratiques, et ainsi palier à ce manque actuel de données sur le long-terme. Développés à l'origine pour les régions tempérées et les systèmes de production pour lesquels les conditions de culture sont optimales (en termes de fourniture d'eau et de nutriments), ces modèles de culture, pour être utiles, doivent être testés et calibrés pour les systèmes tropicaux à faible niveau d'intrants.

J'ai coordonné un projet AGMIP évaluant les modèles de simulation de la croissance du maïs existants, dans les contextes des petites exploitations agricoles familiales de l'Afrique sub-Saharienne. L'étude a impliqué 25 groupes de modélisation et les résultats ont montré une variabilité significative dans la précision des modèles, soulignant l'importance de la calibration à partir de données de terrain pour réduire l'incertitude des prédictions. Cette étude a également permis de confirmer que les effets du changement climatique sont plus prononcés lorsque les apports en nutriments sont plus importants. Les agriculteurs d'Afrique au sud du Sahara seront donc plus vulnérables face aux effets du changement climatique, à mesure qu'ils intensifient leur système de culture. L'étude a également permis de mettre en évidence le fait que des conditions plus humides et des pluies plus intenses provoquaient le lessivage de l'azote, ce qui réduisait les rendements en l'absence d'application d'engrais.

La mesure dans laquelle les modèles de culture ont été testés et améliorés dépend de l'option d'intensification durable envisagée. Les études abondent sur la simulation de l'impact i) des variétés améliorées (par exemple, avec une durée plus courte ou une sensibilité contrastée à la photopériode) et ii) de l'utilisation contrastée d'intrants azotés. La diversification avec des légumineuses (par exemple, par la culture associée de céréales et de légumineuses ou par la rotation avec des engrais verts) et la gestion intégrée de la fertilité des sols (combinaison d'apports minéraux et organiques) ont fait l'objet d'un examen moins approfondi. Comme mes recherches se sont concentrées sur l'impact de ces options face à la variabilité climatique, j'ai consacré une part importante de mes activités de recherche à tester les modèles de culture pour leur capacité à gérer l'intégration des légumineuses dans les systèmes de culture.

J'ai ainsi contribué à démontrer la capacité du modèle sol-culture STICS à simuler avec précision les performances d'une gamme d'options de légumineuses : STICS a pu simuler l'impact du stress hydrique sur la fixation de l'azote, ce qui s'est avéré expliquer une grande partie de la variabilité observée dans la fixation de N₂ atmosphérique par la féverole dans le sud de la France. Le modèle s'est également avéré utile pour reproduire l'impact de l'incorporation d'engrais verts sur l'absorption d'azote par le

riz dans les hautes terres subhumides de Madagascar. L'impact de la culture associée du sorgho et de niébé sur la productivité des terres dans le sud du Mali a également été bien reproduit par la version 'culture associée' de STICS. STICS a également été calibré de manière robuste pour le mil au Sénégal et, bien qu'il n'ait pas été validé par des observations, il pourrait être utile pour étudier l'impact des parcs agroforestiers à *Faidherbia albida* sur la croissance du mil. En ce qui concerne la gestion intégrée de la fertilité, nous avons montré que les modèles actuels pouvaient reproduire avec précision la dynamique des rendements des cultures et du carbone du sol sur le long terme, à condition que des observations soient disponibles pour une calibration locale. Ce travail a montré que l'incertitude dans la prévision des changements à long terme du carbone du sol augmentait avec le temps, en raison des incertitudes dans la simulation i) des apports racinaires au sol et ii) de l'apport d'azote minéral par la minéralisation de la matière organique du sol et des amendements organiques.

Grâce à ces efforts de calibration des modèles en relation avec les options de diversification et de gestion intégrée de la fertilité, j'ai pu contribuer à la construction et à l'exécution d'expériences virtuelles qui ont révélé les avantages et contraintes de ces options pour la résilience face au changement climatique. Au cours d'études réalisées par des doctorants ou postdocs que j'ai encadrés, nous avons ainsi pu constater que si la diversification des cultures au moyen de légumineuses (par exemple, cultures associées ou engrais verts) permettait d'améliorer la fertilité des sols, ces stratégies ne renforçaient pas toujours la résilience face à la variabilité climatique. Dans le cadre du sud Mali, zone semi-aride, les cultures associées ne permettent pas de stabiliser les rendements lorsque les apports de nutriments augmentent. Dans les hautes terres subhumides de Madagascar, la culture d'un engrais vert n'a pas apporté les bénéfices escomptés en termes de stabilisation des rendements, en raison du lessivage de l'azote fourni par l'engrais vert dans le cas d'années particulièrement pluvieuses. Dans le cas du riz pluvial au Sénégal, des pratiques plus conventionnelles, telles que l'utilisation de variétés de cultures tolérantes au stress et de cultivars à plus longue durée de vie, se sont avérées plus fiables pour l'adaptation au changement climatique.

Thème 3 : Intégrer les contraintes et les opportunités au niveau de l'exploitation agricole dans l'analyse de la transition des systèmes vers une intensification durable

Les exploitations agricoles d'Afrique subsaharienne sont très hétérogènes en termes de ressources, de productivité de la terre et du travail, d'objectifs et de contraintes. La disponibilité en ressources et la productivité des terres sont très souvent étroitement liées, comme le montre le cas des producteurs de coton dans le sud du Mali. Cependant, une productivité de la terre similaire peut masquer une productivité du travail et une autosuffisance alimentaire contrastées, en raison d'un rapport terre/travail disponible différent. En Tanzanie, une enquête ménage représentative au niveau national montre l'énorme variabilité des disponibilités alimentaires à l'échelle du ménage. Les cultures produites et consommées à la ferme sont celles qui contribuent le plus à la disponibilité alimentaire des ménages en situation d'insécurité alimentaire en Tanzanie. En Ouganda, une analyse similaire a montré que ce sont les revenus non agricoles et les ventes de bétail et de produits agricoles qui contribuent le plus à la sécurité alimentaire des ménages agricoles.

J'ai contribué à mettre en évidence le besoin critique de tenir compte du niveau de ressources, des objectifs et des contraintes des exploitations agricoles lors de l'examen des options d'intensification durable. En prenant l'exemple des systèmes agricoles du sud du Mali, où la terre est une ressource limitante, j'ai étudié l'impact de la diversification des terres cultivées sur l'autosuffisance alimentaire et la marge brute, en utilisant les performances des options quantifiées par des expérimentations chez

les agriculteurs, et une simple analyse *ex-ante* à l'échelle de l'exploitation. J'ai constaté que les exploitations faiblement dotées en ressources ne pouvaient pas se permettre de remplacer plus de 40 % de leur superficie de sorgho par du soja sans compromettre leur autosuffisance alimentaire. Avec une telle stratégie de diversification (vers le soja à haute valeur ajoutée), l'augmentation de la marge brute équivaut au coût d'un âne. Au contraire, les agriculteurs disposant de ressources moyennes seraient en mesure de remplacer 100 % de leur sorgho par du soja, sans compromettre leur autosuffisance alimentaire. Cela conduirait à une augmentation plus importante de la marge brute (équivalant au coût d'un bœuf supplémentaire, un actif très important pour la préparation des sols). Des options similaires ont donc donné lieu à des opportunités contrastées pour différents types de d'exploitation agricole. Dans le contexte de l'Afrique de l'Est, une analyse portant sur un ensemble d'exploitations agricoles, représentatifs au niveau national en Tanzanie et en Ouganda, a montré que l'intensification de la production de maïs avec davantage d'engrais minéraux profitait davantage (en termes d'augmentation de la disponibilité alimentaire) aux ménages en situation d'insécurité alimentaire qu'aux ménages en situation de sécurité alimentaire. Ces deux exemples montrent qu'il est essentiel de prendre en compte les contraintes au niveau de l'exploitation pour une meilleure intégration des stratégies d'intensification durable.

Alors que les résultats au niveau de la parcelle (par exemple, les augmentations de rendement, de marge brute) peuvent être substantiels, une analyse au niveau de l'exploitation conclut souvent à des avantages très limités. Ceci est illustré par l'exemple de la zone cotonnière du sud du Mali, où une transition très ambitieuse pour tous les agriculteurs vers la culture associée maïs-légumineuse, et l'alimentation des vaches laitières avec le fourrage produit sur l'exploitation, n'a amélioré que marginalement le revenu des agriculteurs et l'autosuffisance alimentaire. Une part importante de la population agricole resterait en situation d'insécurité alimentaire et en dessous du seuil de pauvreté à l'horizon 2030, en raison de la croissance démographique. L'étude a montré qu'un développement socio-économique (par exemple, la planification familiale et la création d'emplois en dehors de l'agriculture) était nécessaire pour permettre à l'ensemble de la population agricole de dépasser le seuil de pauvreté.

Thème 4 : Évaluer les possibilités d'extrapolation de résultats locaux au niveau régional/pays

Les performances des options d'intensification durable dépendent fortement du contexte et sont influencées par des facteurs tels que le sol, le climat et le type d'exploitation agricole. Cependant, ces résultats sont souvent issus d'études locales à la portée limitée, ce qui empêche des recommandations à grande échelle pour la prise de décision. Pour y remédier, j'ai contribué à l'élaboration d'études qui étendent les résultats ponctuels à des échelles plus larges.

Dans un article récent, j'ai utilisé un modèle de forêt aléatoire, à partir de plus de 15 000 observations sur la réponse du maïs aux engrais minéraux en Afrique, pour prédire cette réponse en fonction des caractéristiques du sol. Le modèle a ensuite été utilisé pour évaluer l'impact de l'intensification du maïs sur la sécurité alimentaire des ménages en Ouganda et en Tanzanie. Les résultats ont montré que l'intensification pour les grandes exploitations améliorait l'approvisionnement national en maïs, mais que les petites exploitations souffrant d'insécurité alimentaire bénéficiaient davantage en termes de sécurité alimentaire à l'échelle du ménage.

J'ai également collaboré à une étude qui montre qu'au Sénégal, pays semi-aride, l'intégration de données sur le couvert végétal des arbres a permis d'améliorer les prévisions de rendement du mil à

l'aide de modèle de machine learning. Cela démontre que la configuration du paysage, et pas seulement les interventions au niveau de la parcelle, est cruciale pour l'intensification durable.

Les études susmentionnées en Ouganda, en Tanzanie et au Sénégal s'appuient sur des cartes numériques des sols pour l'exploration spatiale de l'impact des options d'intensification durable sur la productivité des cultures. Ces cartes sont très utiles, mais elles manquent parfois de pertinence locale (par exemple elles sous-estiment les stocks de carbone observés pour certains types d'usage des terres). J'ai contribué à une étude qui décrit des pistes pour améliorer ces cartes : il est possible d'augmenter les ensembles de données d'entraînement des modèles utilisés pour l'interpolation des données pédologiques. Les mesures de sol pour des homosols, c'est-à-dire des localités partageant des facteurs de formation du sol similaire (mais potentiellement très éloigné géographiquement), peuvent être utilisés pour l'entraînement du modèle et améliorer ainsi sa précision.

Dans une autre étude que j'ai coécrite, nous avons identifié des régions favorables en Afrique de l'Ouest pour des pratiques telles que la culture associée et le paillage à l'aide des résidus de culture, en réalisant une carte des facteurs biophysiques (pluviométrie et utilisation des terres), socio-économiques (densité de population et densité du bétail), mais également institutionnels (tels que les plans d'adaptation nationaux au changement climatique).

C) Projet de recherche

Mes recherches antérieures ont permis de comprendre où les options d'intensification durable peuvent profiter aux petits exploitants agricoles, d'identifier les obstacles à l'adoption au niveau de l'exploitation, et d'explorer certaines possibilités d'extrapolation au niveau régional. Toutefois, ces données et résultats d'étude restent fragmentaires. Bien que les études locales offrent des perspectives adaptées au contexte, leur applicabilité plus large (régions, grand nombre de ménages agricoles), n'est pas claire. Par exemple, les sols dégradés peuvent ne pas répondre aux applications de nutriments, et les études documentant ce défi sur différents sites en Afrique subsaharienne abondent. Toutefois, on ne sait pas dans quelle mesure ce type de sols dégradés est répandu en Afrique, ni combien de ménages ruraux sont touchés, ni dans quelle mesure cela aura un impact sur le potentiel d'augmentation des disponibilités alimentaires sur le continent. De même, les engrais verts et les plantes de couverture se sont avérés utiles pour réduire les besoins en engrais minéraux sur des sites contrastés dans les zones semi-arides et subhumides de l'Afrique subsaharienne. Mais l'adoption de cette pratique par la majorité des agriculteurs permettrait-elle de réduire sensiblement les impacts négatifs cumulés des engrais sur l'environnement ?

L'extrapolation des résultats de l'intensification durable à l'échelle de la parcelle se heurte à une série de difficultés. Les méthodes 'top-down' qui utilisent des données géographiques globales pour simuler des résultats locaux manquent souvent de calibration, ce qui se traduit généralement par des prévisions peu fiables pour les contextes africains. En revanche, les approches 'bottom-up', qui extrapolent les données locales à des zones similaires en termes de contexte agroécologique et socio-économique, sont sous-utilisées en Afrique. De plus, les modèles de culture se concentrent principalement sur les variétés améliorées et les engrais, et qu'ils ont négligé des options essentielles d'intensification durable telles que les cultures associées et l'agroforesterie.

Le niveau de l'exploitation agricole est également crucial pour l'intensification durable, car les contraintes et les opportunités des exploitations agricoles vont au-delà des facteurs biophysiques, et implique des considérations telles que la demande de main-d'œuvre et les revenus non agricoles. La

cartographie de la diversité des exploitations est complexe, les variations locales dépassant souvent les variations nationales. Les enquêtes nationales sur les ménages, telles que LSMS-ISA et RHOMIS, permettent d'analyser les caractéristiques des ménages, mais ces enquêtes grossières manquent de détails pour évaluer avec précision les pratiques nécessaires pour combler les écarts de rendement ou s'attaquer aux contraintes en matière de main-d'œuvre et de liquidités. Des modèles bioéconomiques plus détaillés, bien que souvent limités en termes de couverture spatiale, peuvent aider à examiner comment les politiques (par exemple, les subventions, les assurances) affecteraient l'adoption d'options d'intensification durable, et révéler les compromis entre revenu immédiat pour les agricultures, et amélioration de la durabilité environnementale. Une approche hybride combinant de vastes ensembles de données sur les ménages agricoles, avec des enquêtes plus détaillées sur les flux de ressources et la modélisation bioéconomique, est nécessaire pour comprendre les réponses à l'intensification durable, pour une large gamme de types d'exploitations et de régions agroécologiques sur le continent.

L'analyse au niveau de la parcelle et de l'exploitation agricole ne tient pas compte des aspects essentiels de la gouvernance des ressources naturelles et de l'action collective, qui se produisent au niveau du paysage. Par exemple, certaines options d'intensification durable comme le paillage avec les résidus de culture, nécessitent une coopération entre les agriculteurs, notamment pour clôturer les champs afin d'empêcher le pâturage par le bétail, ce qui soulève des questions d'équité entre agriculteurs et agro-éleveurs. L'efficacité des options d'intensification durable, comme le push-pull, dépend également de la complexité du paysage. Le push-pull consiste à cultiver des céréales en association avec une légumineuse qui repousse les ravageurs (« push »), et cultiver autour de la parcelle une plante fourragère qui attire les ravageurs (« pull »). Cette technique est inefficace dans les paysages complexes qui abritent déjà d'abondantes populations de prédateurs naturels.

L'analyse à l'échelle du paysage est également essentielle pour la conservation de la biodiversité. Par exemple, des pratiques telles que la culture associée pour augmenter la production de fourrage, associée à la stabulation des animaux d'élevage, peuvent réduire les besoins d'extension des zones de pâturage, et contribuer ainsi à la conservation d'habitat naturel favorable à un maintien de la biodiversité. Les paysages riches en biodiversité, bien que fournissant des services écosystémiques, peuvent également être à l'origine d'une série de di-services tels que des conflits homme-faune, des dommages aux cultures et la propagation de maladies au bétail. L'intégration de la recherche au niveau du paysage permet de relever plus efficacement les défis de la durabilité et de la conservation de la biodiversité.

Un cadre de recherche pour l'évaluation à plusieurs échelles

À la lumière de cette analyse des principales lacunes en matière de recherche et de méthodologie à l'échelle de la parcelle, de l'exploitation agricole et du paysage, je propose le projet de recherche suivant : « évaluation multi-échelle de la contribution des options d'intensification durable à la sécurité alimentaire, à l'adaptation et l'atténuation du changement climatique, et à la conservation de la biodiversité ». J'explorerai les trois questions de recherche suivantes :

- i) Comment les variations spatiales et temporelles du climat et des sols influencent-elles les performances agronomiques et environnementales des options d'intensification durable ?
- ii) Quels sont les principaux compromis pour l'allocation des ressources au niveau de l'exploitation (argent, travail, terre), et comment cela varie-t-il localement (type d'exploitation) et plus largement à travers le continent (zones agroécologiques) ?

iii) Quelle composition et quelle configuration du paysage sont nécessaires pour concilier la sécurité alimentaire, l'atténuation et l'adaptation au changement climatique et la conservation de la biodiversité ?

Pour répondre à ces questions, je propose un cadre qui articule les trois niveaux d'analyse, à savoir la parcelle, l'exploitation et le paysage. L'objectif global de ce cadre d'analyse est i) de produire des estimations réalistes de la performance des options d'intensification durable au niveau de la parcelle et de la région, ii) de fournir des preuves des barrières et des opportunités (en mettant l'accent sur les incitations politiques) pour leur mise en œuvre dans l'exploitation agricole, et iii) d'évaluer comment ces éléments s'agrègent au niveau du paysage en termes de sécurité alimentaire, d'adaptation au changement climatique et d'atténuation de ses effets, et de conservation de la biodiversité. Ce cadre met l'accent sur l'utilisation de données de terrain issues de sites diversifiés en termes de climats, de sols et de conditions socio-économiques. Les outils analytiques comprennent des modèles de culture, des modèles bioéconomiques et des simulations basées sur des scénarios pour prédire la performance des options et leur potentielle intégration dans l'exploitation et le paysage, pour des sites contrastés. Les résultats typiques comprennent des cartes de performance spatiale, des impacts des subventions au niveau de l'exploitation et des matrices de durabilité basées sur des scénarios d'évolution du contexte socio-économique. La collaboration des acteurs des filières agricoles garantit l'alignement des scénarii explorés avec les besoins locaux, orientant la recherche et la prise de décision au niveau de la parcelle, de l'exploitation et du paysage.

(1) - Variation spatiale et temporelle des performances agronomiques et environnementales des options d'intensification durable

Cette recherche se concentrera sur la compréhension des performances des stratégies de diversification et de gestion intégrée de la fertilité des sols en Afrique sub-Saharienne. Une étude en cours, dirigée par une doctorante, examine le rôle des cultures associées céréales-légumineuses pour améliorer la productivité et la résilience face aux aléas du climat, en utilisant un réseau de sites expérimentaux au Mali et au Sénégal (climats semi-aride), au Burkina Faso et au Zimbabwe (climat subhumide). Cette étude comprendra une calibration approfondie d'un modèle de culture afin d'évaluer les bénéfices à large échelle des cultures associées et leur impact sur la biodiversité (grâce à la limitation de l'extension des terres cultivées) sur l'ensemble du continent. En outre, une étude doctorale qui débutera l'année prochaine (financement assuré et candidat identifié) utilisera des modèles de culture pour évaluer les compromis de productivité et de résilience entre le maïs et le sorgho, dans différentes conditions agroécologiques. L'agroforesterie, et en particulier la manière dont les interactions entre les arbres et les cultures affectent la fertilité des sols et les rendements des cultures dans les parcs arborés d'Afrique sub-Saharienne, sera également étudiée. Les collaborations avec des partenaires tels que le CIMMYT et dans le cadre du nouveau projet financé par l'UE « Renforcer les moyens de subsistance ruraux et la résilience au changement climatique en Afrique : agroforesterie innovante intégrant les personnes, les arbres, les cultures et le bétail » (Galileo) seront mises à profit pour cartographier les impacts des parcs agroforestiers sur la productivité des cultures, et explorer comment les changements futurs de la densité de ces parcs peuvent influencer le disponible en nourriture.

Parallèlement, je dirige une étude sur la gestion intégrée de la fertilité des sols qui vise à évaluer la variabilité des réponses aux engrais pour la production de maïs. L'étude utilise la modélisation spatiale pour i) cartographier les risques liés à l'intensification de la production agricole, et ii) identifier les zones prioritaires pour l'implémentation de stratégies d'atténuation des risques, telles qu'irrigation ou assurance des récoltes. En complément, les efforts en cours dans le cadre du projet RAIZ et le

partenariat avec des collègues de mon équipe de recherche permettront d'étudier comment les prévisions météorologiques peuvent aider à optimiser les décisions de gestion des cultures. Enfin, nous développons actuellement un projet dans lequel un postdoc sera chargé de tirer parti des essais de fertilisation existants pour cartographier (à l'aide de modèles d'apprentissage automatique) l'étendue des sols qui ne répondent pas à l'application de nutriment dans toute l'Afrique subsaharienne.

(2) - Quels sont les principaux compromis pour l'allocation des ressources au niveau de l'exploitation, et comment cela varie-t-il localement et plus largement à travers le continent ?

Une nouvelle activité de recherche menée avec des collègues de mon unité de recherche se concentrera sur l'évaluation des possibilités d'intégrer davantage de légumineuses dans les systèmes agricoles, afin de réduire l'utilisation d'engrais et améliorer les performances environnementales. L'étude portera sur la manière dont les facteurs économiques externes et les types d'exploitations agricoles influencent l'adoption des légumineuses, dans diverses régions d'Afrique subsaharienne (Sénégal, Burkina Faso, Zimbabwe), et en Asie du Sud-Est (Laos). Un modèle bioéconomique simple sera utilisé pour évaluer les décisions d'allocation des cultures aux terres disponibles, en fonction de la productivité, rentabilité et demande en main d'œuvre des différents systèmes de culture. Les enquêtes auprès des ménages indiquent qu'actuellement, l'intégration des légumineuses dépasse rarement 25 % de la surface cultivée. Des scénarios exploreront la manière dont des subventions ou des paiements pour services écosystémiques pourraient stimuler l'intégration des légumineuses, en identifiant les régions où l'incitation politique est la plus efficace. La recherche contribuera à mettre en évidence la nécessité d'un soutien public et d'incitations économiques pour promouvoir avec succès les pratiques d'intensification durable.

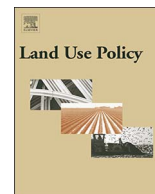
Résultats attendus pour (3) - Quelle composition et quelle configuration du paysage permettent de concilier la sécurité alimentaire, l'adaptation et l'atténuation du changement climatique, et la conservation de la biodiversité ?

En partenariat avec un doctorant, une recherche en cours examine comment les différents types d'usage et d'occupation des terres ont un impact sur la sécurité alimentaire, l'atténuation du changement climatique et la conservation de la biodiversité, au Zimbabwe. Des scénarios de paysages futurs ont été élaborés en collaboration avec les agriculteurs, en tenant compte de facteurs externes tels que le climat et les conditions économiques. Les modèles ad-hoc développés permettront d'évaluer des indicateurs tels que l'autosuffisance alimentaire, la disponibilité du fumier, les stocks de carbone dans les sols et la biodiversité. Les résultats préliminaires ont montré que l'extension de la culture du tabac ou des céréales conduit à une réduction de la couverture forestière, quel que soit le scénario d'évolution des facteurs externes. Cela permet d'identifier des stratégies « sans regret », par exemple la mise en défens de parcelles forestières.

Le travail du doctorant ne porte actuellement que sur un seul site d'étude de cas. Les comparaisons entre sites permettront d'identifier i) les principaux problèmes de durabilité (mauvaise performance pour un indicateur donné, quel que soit le contexte externe) et ii) les actions collectives nécessaires. Certaines stratégies pourraient être pertinentes pour tous les sites, tandis que d'autres peuvent ne fonctionner que dans certains d'entre eux ; ces conclusions seront essentielles pour définir les priorités quant au type d'interventions à privilégier.

Il existe des possibilités d'expansion d'une approche similaire à celle menée par le doctorant sur un autre site au Zimbabwe en climat semi-aride, près du parc national de Mana-Pools - où les conflits homme-faune sont un problème clé.

REPRINTS OF SELECTED PUBLICATIONS



Agricultural intensification and policy interventions: Exploring plausible futures for smallholder farmers in Southern Mali

Gatien N. Falconnier^{a,*}, Katrien Descheemaeker^b, Bouba Traore^c, Arouna Bayoko^d, Ken E. Giller^b

^a UMR AGIR, Université de Toulouse, INPT, INP-PURPAN, INRA, 31320 Castanet Tolosan, France

^b Plant Production Systems, Wageningen University, P.O. Box 430, 6700 AK Wageningen, The Netherlands

^c International Crops Research Institute for the Semi-Arid Tropics (ICRISAT-Mali), BP 320 Bamako, Mali

^d Association Malienne d'Eveil au Développement Durable (AMEDD), Darsalam II, Route de Ségou, BP 212 Koutiala, Mali

ARTICLE INFO

Keywords:

Farm typology

Yield gap

Rural-urban migration

Net fertility

ABSTRACT

Assessing how livelihoods in rural sub-Saharan Africa might change given future trends in socio-economic and biophysical conditions helps to identify and direct effective efforts towards poverty reduction. Based on existing literature, hypothetical changes in farmer practices and policy interventions were described and used to build five contrasting scenarios towards the year 2027. A simulation framework was developed to assess food self-sufficiency and income per capita now and in the future for a representative village of 99 households in Southern Mali. In the current situation, 26% of the farms were food self-sufficient and above the 1.9 US\$ day⁻¹ poverty line. This percentage would fall to 13% in the “Business as usual” scenario. In the “Dairy development” scenario, with intensification of livestock production and support to the milk sector, 27% of farms would be food self-sufficient and non-poor. Additional policy interventions targeting family planning and job creation outside agriculture would be needed to improve both household food self-sufficiency and income per capita. In this optimistic scenario, 77% of the farms would be non-poor and food self-sufficient in 2027. Additional programs to promote Integrated Pest Management, small-scale mechanization and mineral fertilizer on traditional cereals could allow a drastic increase in productivity and would lift 94% of the farm population out of poverty. Considering the entire heterogeneous farm population was crucial to accurately assess pathways out of poverty. Our study stresses the need for a strategic and multi-sectoral combination of interventions to improve livelihoods.

1. Introduction

The human population in Africa is growing faster than in other continents and will account for more than half of the growth in the world's population between now and 2050 (United Nations, 2015). In many regions across sub-Saharan Africa there is no land suitable for further agricultural expansion, therefore farm size is decreasing (Harris and Orr, 2014). Faced with land shortage and the challenge to produce sufficient food, farmers can respond in three ways: intensifying agricultural production, migrating out of agriculture and/or reducing human fertility rates (Headey and Jayne, 2014). Policy interventions can favour these strategies, as examples from around Africa illustrate: large scale agricultural input subsidy programs improved land productivity in Malawi (Dorward and Chirwa, 2011). Educational investment targeting rural areas and creation of non-agricultural wage jobs in the cities favoured rural-urban migration in Uganda (de Brauw et al., 2014; Fox and Sohnesen, 2012). In Rwanda and Kenya, subsidized

contraceptive services and education campaigns triggered the transition from high to low birth rates (Bongaarts, 2011). Yet the pace and the magnitude of the effects of such policy interventions are difficult to foresee (Thompson and Scoones, 2009). In Mali, achieving food self-sufficiency and poverty reduction are the key objectives of the latest “Loi d’Orientation Agricole” (LOA) (<http://www.pcda-mali.org/site/index.php/29-mediathèque/31-la-loi-d-orientation-agricole-du-mali-loa>, last accessed 19/02/2016). Hence assessing how income and food production might change under uncertain future socio-economic and biophysical conditions may generate useful information for directing policy interventions towards poverty reduction.

Scenarios help to capture uncertainty by defining plausible futures covering a range of socioeconomic and biophysical conditions (O'Neill et al., 2017). Many studies built scenarios based on hypothetical changes in population, policy interventions and efficiency of institutions and assessed their effect on land use change, intensification and diversification of agriculture (Enfors et al., 2008; Stephenne and

* Corresponding author.

E-mail addresses: ffalconniergatien@yahoo.fr, gatien.falconnier@inra.fr (G.N. Falconnier).

Lambin, 2004). These studies illustrated how scenarios inform decision-making and help to target agricultural development investments. Some of these studies stressed the importance of considering farm heterogeneity to increase the assessment accuracy (García-Martínez et al., 2011; Gibreel et al., 2014; Herrero et al., 2014). However, they focused on land use change and did not quantify changes in food production and income for the different farm types. Scenario work is widespread for developed countries (Bizikova et al., 2015) but remains rare in sub-Saharan Africa, with scarce quantitative information on likely changes in income and food self-sufficiency. Furthermore, beyond future changes in representative farms or farm types, only few studies assess changes in entire diverse farm populations (Descheemaeker et al., 2016; Paul et al., 2017; Ritzema et al., 2017).

The “old cotton basin” in Southern Mali experiences fast population growth and increasing land shortage (Soumaré et al., 2008), common challenges in land constrained regions across sub-Saharan Africa. The region has shown a promising agricultural intensification pathway (1960–2000) linked to cotton production (Benjaminsen et al., 2010), but since the cotton crisis (2004), agricultural productivity has stagnated (Falconnier et al., 2015). Hence the Malian government is committed to increasing agricultural productivity (de la Croix et al., 2011; Kelly et al., 2011) and increasing off-farm opportunities for the youth (African Development Bank, 2012). Yet policy makers need locally grounded information to take effective decisions. Adding to the uncertainty of future trajectories of change, the heterogeneous farms of the region (Falconnier et al., 2015) are expected to respond differently to changes in socio-economic conditions.

The objective of this study was to assess the effects of agricultural intensification, rural to urban migration and net fertility reduction on rural poverty and food self-sufficiency for contrasting plausible mid-term futures (fifteen years ahead) for the entire population of a case study village in the “old cotton basin” of Southern Mali. Specific objectives were to (i) build scenarios that span a wide range of uncertainty in socio-economic futures, (ii) develop a simulation framework that accounts for household demographic dynamics, sensitivity of crops to rainfall variability and change in farmer practices and (iii) assess trends in food self-sufficiency and income per capita for all farms in the village population in the different scenarios.

2. Methods

2.1. Study area

The “old cotton basin” is an area situated in the Sudanian agro-ecological zone of Southern Mali (Coulily, 2003). The rainy season starts in May and ends in October and total rainfall fluctuates from 500 to 1200 mm. The area groups three districts (Koutiala, Dioila and the northern part of Sikasso) and accommodates more than a million of rural people (Traore et al., 2011). Households are extended families comprising the head of the household, his sons and wives and their children (Jonckers and Colley, 1974). Farmers grow cotton, cereals and groundnut in rotation and use manure, mineral fertilizer and oxen for draught power. The Compagnie Malienne pour le Développement des Textiles (CMDT) buys the cotton and provides credit for mineral fertilizer for cotton and maize (Falconnier et al., 2015).

2.2. Datasets

The “Suivi Evaluation Permanent” (SEP) dataset collected by the “Equipe Système de Production et Gestion des Ressources Naturelles (ESPGRN)” of the Malian Institut d’Economie Rural (IER) contains information on household resource endowment, input use and cotton yields measured by CMDT for 30 farms from three villages of the “old cotton basin” from 1994 to 2010. Farms were classified in four farm types, namely High Resource Endowed with Large Herds (HRE-LH), High Resource Endowed (HRE), Medium Resource Endowed (MRE) and

Low Resource Endowed (LRE) farms according to (1) total cropped land (ha), (2) number of workers, (3) herd size and (4) number of draught tools (Falconnier et al., 2015). LRE farmers usually don’t have a full span of oxen and/or a plough.

Data on resource endowment and crop area in 2013 for the 99 households of the Nampossela village (12°15′ N and 15° 20′ W) was obtained from the CMDT. All households in Nampossela were classified in one of the four HRE-LH, HRE, MRE and LRE farm types. Nampossela is a typical village of the ‘old cotton basin’. It is close (10 km) to the three SEP villages where the farm typology was generated, with very similar agro-ecology, farm practices and marketing opportunities. The share of the four farm types in this village was 12%, 19%, 55% and 14% for HRE-LH, HRE, MRE, LRE farms respectively, which is close to the average share in the Koutiala region (Falconnier et al., 2015).

2.3. Scenario building

Starting from the baseline year 2013, we explored the effects of wide-ranging future agricultural and socio-economic changes within a 15-year time span (2013–2027). Hypothetical trends in agricultural intensification were conceived based on promising agricultural technologies identified for the region. On the policy side, we took into account expected changes in the cotton and milk context described in the literature and policies that would affect birth and migration rates. Key variables were selected to describe these trends and quantified by extrapolating past trends described in the literature. Eventually, combinations of hypothetical trends were bundled into five coherent and contrasting scenarios. We did not consider technological change that would result in increased potential yield due to breeding. Although the 15-year time span corresponds to the ‘near term’ where additional uncertainty due to climate change is assumed to be negligible (Pachauri and Meyer, 2015), climate change is considered an important threat to agriculture in the region (Traore et al., 2017). Hence, to inform decision making towards timely adaptation, we included climate change effects in the sensitivity analysis (Section 2.6).

2.4. Simulation framework

A model framework was built to simulate three major farm components (household, cropland and cattle herd) and their interactions (Fig. 1) for each of the 99 farms of the Nampossela village. The model was run for both a baseline situation (2013) and a near-term future situation 15 years later (2027). The baseline and the future situation were each simulated with the same series of 29 historical seasons (1965–1993), which is the only complete weather dataset for which corresponding water-limited potential cotton yields were observed (see Section 2.4.2). For the baseline and the future situation, food self-sufficiency and income per capita were computed for each farm, averaged across the seasons and for each farm type. Also the year-to-year variability was assessed. Furthermore, the percentage of farms above the poverty line and food self-sufficient was computed for both the baseline and the future situation. Hence, the scenario analysis was not based on a continuous temporal change, but on a comparison of separately modelled baseline and future situations, which is common practice (Miguel Ayala et al., 2016; Rajib et al., 2016). The model was built with the R programming language. Main model input comprised farm characteristics (farm type, area of the different crops, household size, number of tools and animals) and crop/livestock performances (grain, fodder and milk yield) (Fig. 1). Further input to the model comprised net fertility and migration rates and farm and socio-economic conditions derived from the scenarios. More details on parameters, input, output variables and calculations are available in supplementary material as background and resource for readers who are interested to repeat this exercise. In what follows we explain each model component and indicator separately.

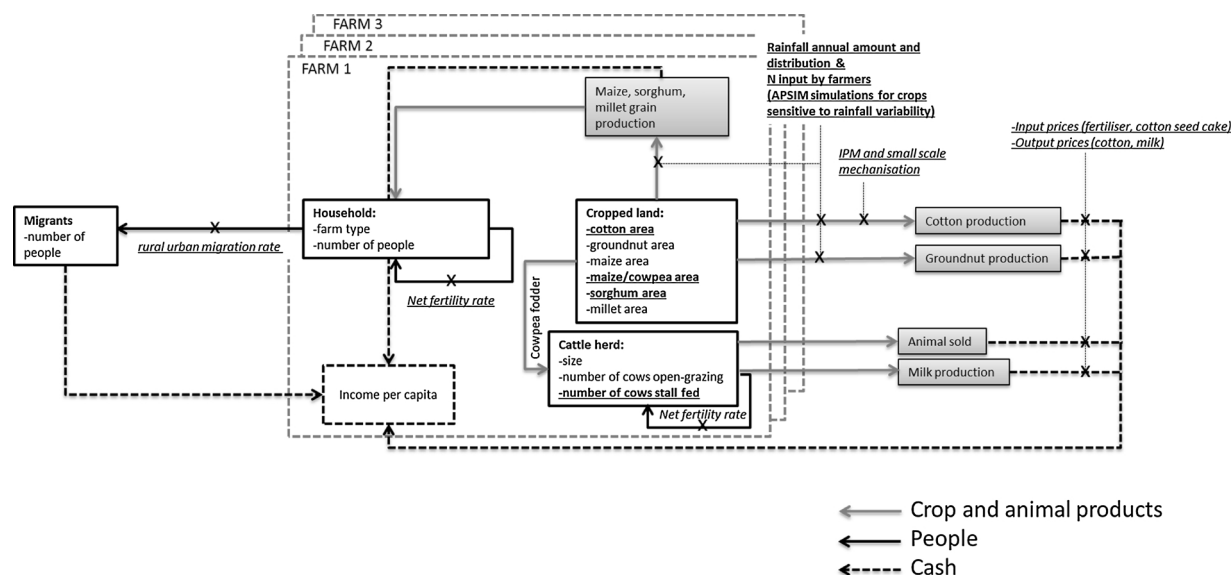


Fig. 1. Conceptual framework for simulations of farms with three components: household, cropped land and cattle herd. Arrows symbolize flows of crop and animal products, people and cash. Underlined, the key agricultural (bold) and policy (italics) variables identified and quantified for five scenarios of agricultural intensification and policy intervention (Fig. 2 and Table 1 give a detailed description of the scenarios). Only three farms are depicted but in reality 99 farms are simulated.

2.4.1. Household component

Number of people in each household (Fig. 1) in 2013 ($HH_{size_{2013}}$) was obtained from the village survey data. For each farm, household size in 2027 ($HH_{size_{2027}}$) was calculated as follow:

$$(1) HH_{size_{2027}} = HH_{size_{2013}} [1 + (fertility_{rate} - migration_{rate})]^{2027-2013}$$

where *fertility_rate* is the net (birth-death) fertility rate and *migration_rate* is the rural to urban migration rate. Fertility rates were specific for each scenario, while migration rates were specific for each scenario and farm type. For each of the four farm types, past average annual growth rate of the household size was calculated using 1994 and 2010 SEP data. Rural-urban migration rate over the 1994–2010 period was estimated as the difference between the observed annual growth rate of household size and the Malian average net fertility (birth-death) rate (3.4%) (World Bank, <http://data.worldbank.org/indicator/SP.DYN.CBRT.IN>, last accessed 30/09/2016).

Traditionally, the eldest son inherits the land and becomes the head of the household (comprising the younger brothers), which prevents land subdivision (Jonckers and Colleyn, 1974) except if brothers disagree. The SEP data showed that only one out of 30 households was subdivided during the whole 1994–2010 period (Falconnier et al., 2015). In line with this finding, a comprehensive survey carried out in 2006 showed that 71% of the 146 farms of another village in the Koutiala district originated from a traditional inheritance process without land holding subdivision and only 29% originated from a household subdivision, with 86% of these subdivisions having occurred before 1996 (Poccard-Chapuis et al., 2007). Hence, as population increase results in a decrease in land per capita rather than a decrease in farm size, landholding subdivision was not considered for the simulations. As there is no arable land available for expansion (Falconnier et al., 2015), total cropped land per household (Fig. 1) was kept constant over the 15 years of the simulation.

2.4.2. Cropped land component

Information on cropland allocation and area (Fig. 1) in the baseline was obtained from the village survey data. To estimate crop yields with farmer practice as a function of variable rainfall and assess year-to-year variability, we used an empirical approach based on experimental results from the region. Correlations between annual rainfall and yield of cotton, maize, sorghum, millet and groundnut were analysed using

published studies reporting measured yield with farmer practices in on-station and on-farm trials in the “old cotton basin”. Additionally, cotton yield measured by CMDT in the SEP dataset were analysed. For the crops for which our literature study indicated a significant effect of rainfall on the yield with farmer practice, this yield was simulated using the APSIM model (Keating et al., 2003) and used as an input to the cropland component (Fig. 1). APSIM was calibrated for a typical Lixisol (FAO, 2006), the cultivars used by farmers in the “old cotton basin” (Traore, 2014; Akinseye, personal communication; Nenkam, personal communication) and run with N application rates used by farmers (derived from SEP data). The yields were simulated using the 1965–1993 weather records from N'Tarla station (Traore et al., 2013). For crops without a significant effect of rainfall on yield, the average measured yield in farmer conditions was used and kept constant for all seasons.

With respect to water-limited potential yields (van Ittersum et al., 2013), cotton yields measured from 1965 to 1993 in the N'Tarla experimental station in plots receiving 90 kg N ha⁻¹ mineral fertilizer and 12.8 t dry matter manure ha⁻¹ were used (Ripoche et al., 2015). For maize, sorghum and millet, yields were simulated with APSIM using the same settings as above and increasing amount of nitrogen. A nitrogen input of 200 kg N ha⁻¹, spread over two applications, was found to release N constraints in all years of the simulation and was therefore used for the determination of the water-limited potential yield. Finally, 85% of the water-limited potential yield and the required N input were determined, corresponding to the exploitable yield gap (van Ittersum et al., 2013).

2.4.3. Cattle herd component

A 10% net fertility rate for cattle (Fig. 1) was assumed (Ba et al., 2011). Annual animal off-take was assumed to be equal to this net fertility rate to ensure a stable cattle herd size (Ba et al., 2011). Current cattle herd size for each household was obtained from the village survey data. The proportion of lactating cows in the cattle herd was assumed to be 22 and 34% for cattle herds below and above 23 animals respectively (Ba et al., 2011). Year-round milk production of cows with open-grazing (current farmer practice) and stall feeding (2.5 kg cowpea hay cow⁻¹ day⁻¹ and 2 kg cotton seed cake cow⁻¹ day⁻¹ during the dry hot period of 90 days) was obtained from De Ridder et al. (2015).

Table 1
Effect of annual rainfall variability on crop yield (according to seven studies of on-farm and on-station measured yields with farmer practice in southern Mali), average yield with current farmer practice and 85% of water limited yield retained for this study. HRE-LH: High Resource Endowed farms with Large Herds, HRE: High Resource Endowed farms, MRE: Medium Resource Endowed farms, LRE: Low Resource Endowed farms (standard deviation in brackets).

Crop	Effect of rainfall on-station yield			Effect of rainfall on-farm yield			Average yield (kg/ha) with current farmer practice						85% of water limited potential yield (kg/ha)					
	P	R ²		P	R ²		HRE-LH	HRE	MRE	LRE	HRE-LH	HRE	MRE	LRE	HRE-LH	HRE	MRE	LRE
Cotton	< 0.05 ^{1,2,4}	0.56 ¹	0.62 ²	> 0.05 ^{1,7}	–	–	1050 ⁶	940 ⁶	910 ⁵	750 ⁵	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)	2220 ⁴ (± 599)
Maize	< 0.05 ²	0.37 ²	–	< 0.05 ³ ; < 0.01 ⁵	–	–	3480 ⁸ (± 190)	3480 ⁸ (± 190)	3480 ⁸ (± 190)	2700 ^b (± 125)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)	4630 ^c (± 680)
Maize in maize/cowpea intercropping	–	–	–	> 0.05 ⁵	–	–	3654 ^e (± 190)	3654 ^e (± 190)	3654 ^e (± 190)	2835 ^e (± 125)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)	4860 ^e (± 680)
Cowpea fodder in maize/cowpea intercropping	–	–	–	–	–	–	1380 ⁵	1380 ⁵	1380 ⁵	1380 ⁵	–	–	–	–	–	–	–	–
Sorghum	> 0.05 ^{1,2,4}	–	–	> 0.05 ⁵	–	–	1030 ⁵	1030 ⁵	1030 ⁵	1030 ⁵	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)	2060 ^d (± 320)
Millet	> 0.05 ²	–	–	> 0.05 ³	–	–	850 ³	850 ³	850 ³	850 ³	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)	1730 ^d (± 510)
Groundnut	> 0.05 ¹	–	–	–	–	–	530 ⁵	530 ⁵	530 ⁵	530 ⁵	–	–	–	–	–	–	–	–

¹ Traore et al. (2013).

² Traore et al. (2014).

³ Traore et al. (2015).

⁴ Ripoché et al. (2015).

⁵ Falconnier et al. (2016).

⁶ Falconnier et al. (2015).

⁷ This study.

^a APSIM simulation with a fertilizer application of 60 kg N ha^{−1}.

^b APSIM simulation with a fertilizer application of 40 kg N ha^{−1}.

^c APSIM simulation with a fertilizer application of 110 kg N ha^{−1}.

^d APSIM simulation with a fertilizer application of 150 kg N ha^{−1}.

^e APSIM simulated maize yield multiplied by 1.08, i.e. the maize partial Land Equivalent Ratio for intercropping when grown after cotton (Falconnier et al., 2016).

Table 2
Key variables and their quantification in the current (2013) and future (2027) situation for hypothetical policy interventions (P0–P4) and hypothetical changes in agricultural practices (A0 to A3). “*” indicates the variables included in the sensitivity analysis.

Key variables	Trend	Variable values		Reference used to build the trend
		2013	2027	
Hypothetical policy interventions				
No input/output subsidy for cotton production (P0)	Decrease	250	183	Coulibaly et al. (2015)
Input/output subsidy for cotton production (P1–P4)	Increase	12500	17500	Coulibaly et al. (2015)
No Input/output subsidy for milk production (P0 and P1)	No change	250	250	Village survey data
Input/output subsidy for milk production (P2–P4)	No change	12500	12500	Village survey data
No family planning programs (P0–P2)	No change	250	250	Village survey data
Family planning programs (P3 and P4)	No change	170	170	Village survey data
	Increase	250	400	Aparisi et al. (2012)
	Decrease	170	50	Kelly et al. (2010)
	Current rate	3.4 (over the period)		World Bank
	Lower rate	2.2 (over the period)		Ministère de la santé et de l'hygiène publique (2014)
Limited job creation outside agriculture (P0–P2)	Current rates	0;1;7;1;2;2.8 (over the period)		SEP data
Important job creation outside agriculture (P3 and P4)	Higher rates	2.8;2.8;2.8; 2.8 (over the period)		African Development Bank (2012)
Integrated Pest Management programs for cotton production (P4)	–	No programs	Programs in place	Silvie et al. (2013)
Incentive subsidy for the development of private small-scale mechanization services (P4)	–	No subsidy	Subsidy	Baudron et al. (2015) and de la Croix et al. (2011)
Fertilizer subsidy for sorghum and millet (P4)	Decrease	17500	12500	Coulibaly et al. (2015)
Hypothetical change in agricultural practices				
Decreasing cotton cultivation (A0)	Decrease ^b	31;32;21;24	22;11;5;8	Falconnier et al. (2015)
No change in farmer practices (A1)	Decrease	43;40;0;0 ^c	43;40;0;0	Falconnier et al. (2015)
	No change	31;32;21;24	31;32;21;24	SEP data
	No change	43;60;0;0 ^a	43;60;0;0 ^a	SEP data
	No change	0	0	SEP data
	No change	0	0	SEP data
	No change	0	0	SEP data
	No change	0	0	SEP data
	Increase	0	100 ^d	SEP data
	Increase	0	100 ^d	Falconnier et al. (2016)
	Increase	0	0–100 ^e	De Ridder et al. (2015)
	Increase	43;60;0;0	90;110;150;150	This Study
	Increase	No	Yes	Silvie et al. (2013)
	Increase	No	Yes	Baudron et al. (2015) and de la Croix et al. (2011)

^a HRE-LH: High Resource Endowed farms with Large Herds; HRE: High Resource Endowed farms, MRE: Medium Resource Endowed farms, LRE: Low Resource Endowed farms.

^b cotton is replaced by sorghum.

^c for LRE farms: 43;40;0;0.

^d except LRE farms: 0%.

^e depending on cowpea fodder production.

2.5. Food self-sufficiency and income per capita

Income per capita (Fig. 1) was calculated as an aggregate of (i) farm income, i.e. monetary gross margins from cotton, groundnut, cereals, milk, live-animal sales, and (ii) non-farm income, i.e. remittances sent by migrants and self-employment (sale on the local rural market of local natural products like wood and charcoal, manufactured goods like baskets and jewellery and services like hair-dressing and repairs of farm equipment). Depreciation of animal drawn equipment (plough, weeder, sowing machines, carts and oxen) was deducted from the income. Transfers related to the remuneration of land (renting), labour (working on others' farm) and capital (interest paid for borrowing money), corresponding to 0, 2% and 0.1% of average income respectively (Samake et al., 2008), were considered negligible.

For cereal gross margin, both self-consumption and surpluses were valued at the market price. Income was expressed in 2011 US dollar Purchasing Power Parity (\$PPP), to allow comparison with the international 1.9 \$PPP/day/person poverty line (Jolliffe and Prydz, 2016; Ravallion et al., 2009). The Average Conversion rate between the Malian currency (FCFA) and \$PPP was obtained from the World Bank estimates (http://databank.worldbank.org/data/reports.aspx?Id=edef810f&Report_Name=ICP_2011_V3, last accessed 18/10/2017). Input and output prices (Fig. 1) at the start of the simulation (2013) were obtained from a market survey carried out in 2013 in Namposela. For the end of the simulation period (2027), input and output prices for milk, cotton and cereals depended on the scenarios, while other prices were kept constant.

Food self-sufficiency was calculated as the percent fulfilment of household calorific need by on-farm production of calories. An average calorific need of 2406 kcal/person/day was considered (average across all SEP households using age-sex specific daily needs, following Britten et al., 2006). The calorie supply was computed based on household cereal production, considering an average supply of 3500 kcal kg⁻¹ maize, sorghum and millet grain (FAO: <http://www.fao.org/docrep/t0818e/T0818E0b.htm>, last accessed 02/10/2015).

2.6. Sensitivity analysis

Variation (from –50% to 50%) was applied to the default trend in the key variables describing the scenarios. For example, the default trend in cotton price was a 27% decrease (see Table 2), so that –50% variation and +50% variation in this default trend corresponded to a 14% and 41% decrease in cotton price respectively. Trends in variables were changed one at a time, while keeping others constant (i.e. at their “no change” or “current rate” value, see Table 2).

To factor in the potential (longer-term) effects of climate change, the effect of a decrease in maize, sorghum and millet yield due to an increase in temperature was assessed. We evaluated the future situation (2027) for the different scenarios using APSIM simulated yields for a hypothetical 2040–2069 period. Daily rainfall and temperature data were obtained from five contrasting Global Circulation Models (GCM) and the high-emission 8.5 Wm⁻² radiative forcing scenario (Traore et al., 2017). APSIM yields were averaged across the five GCMs. The effect of these variations on the key output of the model framework (i.e. percent farms food self-sufficient and non-poor in 2027) was assessed.

3. Results

In what follows, we start by giving the results of the literature and data analysis that formed the basis of the hypothetical trends. Then hypothetical trends and scenarios are explained and finally the results of the simulations and sensitivity analysis are presented.

3.1. Past observed population growth and migration rate

In the 1994–2010 period, the average observed annual growth rate

of household size was 3.4 (± 0.13), 1.7 (± 0.78), 2.2 (± 0.6) and 0.6% (± 1.74) for HRE-LH, HRE, MRE and LRE farms respectively. Based on the average net fertility rate of 3.4% for Mali, estimated rural to urban migration rates were 0, 1.7, 1.2 and 2.8% for HRE-LH, HRE, MRE and LRE farms respectively.

3.2. Crop yields

Maize cultivated with farmer practice was sensitive to seasonal rainfall amount in on-station experiments and in on-farm trials (Falconnier et al., 2016; Traore et al., 2013, 2015). Therefore maize yield under current farmer practice was simulated with APSIM and varied with seasonal rainfall conditions and farm type (Table 1). For the diversification trends, maize yield and cowpea fodder production obtained in maize/cowpea intercropping experiments on-farm were considered (Table 1).

On-station experiments showed the sensitivity of cotton yields to seasonal rainfall (Traore et al., 2013). However, cotton yields less in farmers' fields than on station and tends not to be impacted by seasonal rainfall because of pests and weeds (Traore et al., 2013). Analysis of measured yields in the SEP database showed that farmers' cotton yields were not significantly impacted by total rainfall and rainfall distribution, but by manure input ($P = 0.02$) and oxen per worker (which indicates the ability to weed in a timely fashion) ($P < 0.001$), factors that varied per farm type. Therefore, for the current farmer practice the average cotton yield was considered per farm type and kept constant for all the rainfall seasons (Table 1). For sorghum, millet and groundnut no significant correlations were found between yield and seasonal rainfall in on-station and on-farm experiments with farmer practice (Falconnier et al., 2016; Traore et al., 2013, 2015). Also, no effect of farm type was diagnosed. Therefore, for the scenarios with current farmer practices, average yields obtained in on-farm trials with farmer practice were considered (Table 1) and kept constant for all the rainfall seasons.

The simulated water-limited potential yield for the cereals were obtained with increased nitrogen inputs and resulted in an increased sensitivity to rainfall (illustrated by the larger standard deviation in Table 1).

3.3. Policy interventions

Five policy interventions were conceived, from negative (P0) to ‘business as usual’ (P1) to incrementally progressive (P2–P4).

3.3.1. Input and output prices

Policy interventions related to agricultural input and output prices were considered in three domains. Firstly, a continued decline in cotton prices and a structural removal of fertilizer subsidies is not unlikely in the near future (Coulbaly et al., 2015). Based on these projections, a pessimistic hypothetical policy trend (P0) included a steady decline in the cotton price and a steady increase in mineral fertilizer prices (Table 2). In more optimistic projections (P1–P4), the cotton price and fertilizer subsidy would be maintained at the 2011–2015 level (Falconnier et al., 2015). Secondly, in 2008 the high price of milk powder on the world market decreased milk powder importations, obliging dairy industries in Bamako to use more local milk (Aparisi et al., 2012). In combination with the increased popularity of products from local milk (Corniaux et al., 2012), this led to a 10 Fcfa/L/year increase in the price paid to farmers by dairies from 2005 to 2010. Together with the official food sovereignty objective of the LOA and the lobbying by the West African farmer organization “Réseau des Organisations Paysannes et Professionnelles Agricoles” to raise the Common External Tariff of agricultural commodities in the Economic Community of West African States (Laroche Dupraz and Postolle, 2013), this formed the basis of a progressive policy intervention with tariffs on milk powder (P2–P4). Thirdly, the market for cotton by-products is poorly understood (Kelly et al., 2010). However, we hypothesised that in the

favourable policy trends (P2–P4), the cotton seed cake price would decrease to its lowest level observed in 2003 (Kelly et al., 2010). In the other trends, the current low price for milk and high price for cotton seed cake would be continued (P0 and P1).

3.3.2. Socio-economic development

Policy interventions related to socio-economic development were considered in two domains. Firstly the Malian government committed to family planning with a plan aiming at “increasing the rate of contraceptive use in Mali, moving from 9.9% in 2012 to at least 15% by 2018, through the reduction of unmet need for family planning and by targeting teens and young adults (aged 15–24)” (Ministère de la santé et de l'hygiène publique, 2014). Family planning can decrease net fertility rates (Bongaarts, 2011) but the effect of such a program has not been quantified for Mali. Hence, we hypothesised that family planning would lead to a 35% decrease in fertility rates down to the Côte d'Ivoire level of 2.2% (P3 and P4, Table 2). Furthermore creation of jobs outside of agriculture and educational programs to empower rural people can favour rural to urban migration (de Brauw et al., 2014; Fox and Sohnesen, 2012). The Malian government promoted youth employment with the establishment of several programs aimed at training young people and young entrepreneurs in promising sectors (e.g. industry, mining, information and communication technologies) (African Development Bank, 2012). We assumed that the continuation and strengthening of such policy intervention would lead to rural to urban migration rates of 2.8% for all farm types during the 2013–2027 period (i.e. the highest observed rate in the 1994–2010 period) (P3 and P4, Table 2).

3.3.3. Narrowing yield gap

The comparison of water-limited potential yield and actual yield indicated a large yield gap for cotton despite the use of mineral and organic fertilizer by farmers (with 43 kg N ha⁻¹ and 4.9 t ha⁻¹ dry matter manure on average, cotton with farmer practice yielded only 47% of the water-limited potential yield), pointing to important pest and weed pressure. In Mali, various interventions have promoted Integrated Pest Management, and the cotton area with Integrated Pest Management rose from 104 ha in 1994–92500 ha in 2010 (Silvie et al., 2013), representing still only 33% of the total cotton area. To narrow the cotton yield gap, we conceived a policy intervention (P4) geared towards (i) relieving pest and weed constraints, through further Integrated Pest Management programs, i.e. training of farmers to improve spray scheduling (Hillocks, 2014) and (ii) timely land preparation, sowing and weeding of cotton through subsidies for the development of private small-scale mechanization services to alleviate the shortage in land cultivation equipment (Baudron et al., 2015; de la Croix et al., 2011) (Table 2). In addition to that, P4 included the extension of the fertilizer subsidy to sorghum and millet (currently only on cotton and maize) to incentivize farmers to apply more nitrogen on cereals, allowing to reach 85% of water-limited potential yield for maize, sorghum and millet (Table 2). This policy would be similar to the expansion of the “Initiative Riz” undertaken by the Malian government in 2009 to extend fertilizer subsidies to sorghum and millet (Kelly et al., 2011).

3.4. Agricultural intensification

Falconnier et al. (2015) showed that in the unfavourable cotton context of the past decades, the cotton area of HRE-LH, HRE, MRE and LRE farmers decreased by 30, 66, 75 and 66% and was replaced by sorghum. This cotton area shrinkage, alongside a decrease of mineral fertilizer use down to the level of LRE farms was assumed for the less optimistic agricultural change (A0) (Table 2). In the second hypothetical change (A1), no change in farmer practices was assumed (Table 2). A third trend of agricultural intensification (A2) assumed the adoption of maize/cowpea intercropping (i.e. diversification with legumes) and stall feeding of lactating cows (i.e. intensification of livestock

production) using the cowpea fodder produced on-farm (Table 2). This change was based on findings of a series of co-learning cycles involving farmers of the four farm types (HRE-LH, HRE, MRE and LRE) during three years of research in the study area. The co-learning cycles were composed of (i) on-farm testing of intercropping and stall-feeding options by about hundred farmers in nine villages of the Koutiala region, (ii) appraisal of options by farmers, and (iii) farm system re-designs and ex-ante analysis assessed by farmers (Falconnier et al., 2016, 2017). The co-learning process indicated that maize-cowpea intercropping is a low-risk, profitable option, which can be combined with stall feeding of lactating cows for increased milk production without compromising food self-sufficiency of the household.

A final trend towards agricultural intensification (A3) entailed an increase in the use of mineral fertilizer on maize, sorghum and millet up to the level required to reach 85% of potential yields, and adoption by cotton producers of small-scale mechanization and Integrated Pest Management (Table 2).

Fig. 1 gives a comprehensive picture of how the agricultural and policy variables constituting the trends listed in Table 2 impacted the components of the model framework.

3.5. Scenarios

Five scenarios resulted from the logical combinations of the trends in policy and agricultural intensification (Fig. 2). In the “Marginalisation” (S0) scenario, enabling policies disappear and cotton cultivation and fertilizer use decrease. In the “Business as usual” (S1) scenario, current policies supporting cotton are maintained and farmer practices do not change. The other scenarios rely on incremental policy interventions triggering a change in farmer practices toward agricultural intensification. In the “Dairy development” (S2) scenario, policy interventions extend to the milk sector, triggering cropping diversification with legumes and intensification of livestock production. The “Socio-economic development” (S3) scenario builds on S2, with additional family planning to reduce human fertility rates and job creation outside agriculture to favour rural to urban migration. The “Narrowing yield gap” (S4) scenario is the most optimistic scenario with all the previous policy interventions put in place, and additional interventions to narrow the yield gaps.

3.6. Change in food self-sufficiency and income per capita for different scenarios

All farm types were food self-sufficient on average in 2013, with some variation due to the sensitivity of maize to rainfall (Fig. 3). In S0, average food self-sufficiency decreased for HRE-LH and MRE farms but increased slightly for LRE farms. In S1 and S2, average food self-sufficiency in 2027 decreased compared with the baseline 2013 for all farm types. In S3, food self-sufficiency was maintained at around its 2013 level for all farm types. In S4, food self-sufficiency and its variability increased for all farm types.

In 2013, only HRE-LH farms were above the poverty line in all seasons (Fig. 3). In S0 and S1, income per capita decreased (all farm types except LRE farms) and was below the poverty line, regardless of rainfall. In S2, income per capita was maintained at around its 2013 level, except for LRE (increase) and HRE-LH (decrease). S3 allowed all farm types to increase their income compared with 2013 and move above the poverty line in all seasons. In S4, all farm types increased their income per capita compared with the baseline (2013) and stayed non-poor. The variability in income per capita also increased in S4.

In the baseline year (2013), 26% (± 0.5% depending on the rainfall season considered) of farms of the village were non-poor and food self-sufficient (Fig. 4). In S0, S1 and S2 this percentage fell to 6% (± 0.1%), 13% (± 0.3%) and 27% (± 0.2%) respectively. With S3, 77% (± 0.2%) of the farms were non-poor and food self-sufficient, and this percentage further rose to 94% (± 1.4%) in S4.

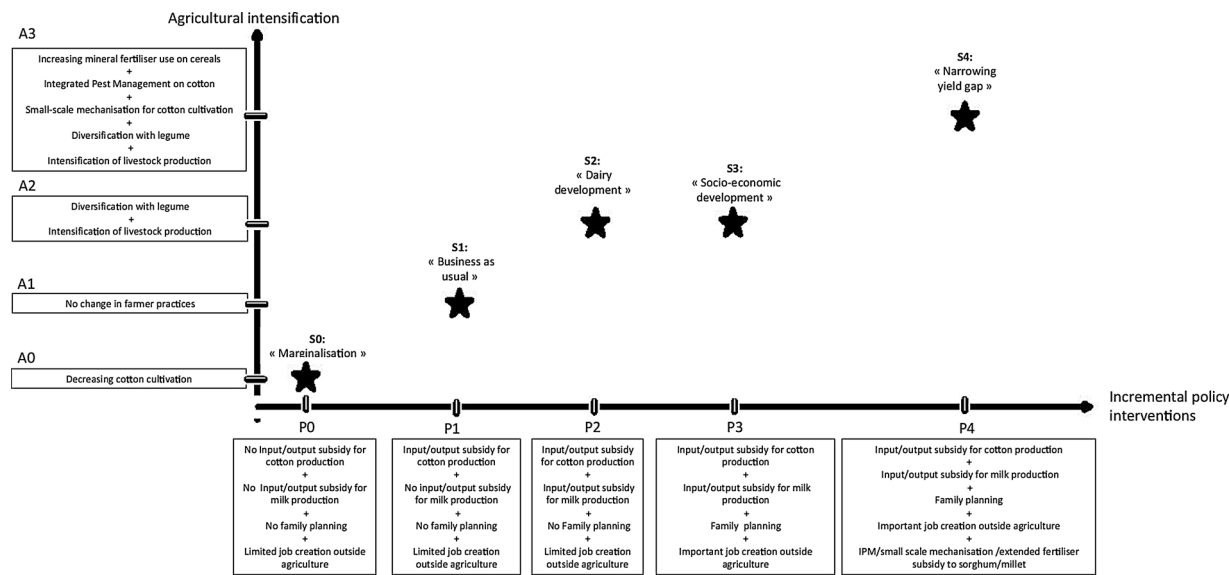


Fig. 2. Illustrative mapping of five scenarios according to hypothetical changes in agricultural practice and policy interventions. Key variables quantifying the hypothetical changes are described in Table 1.

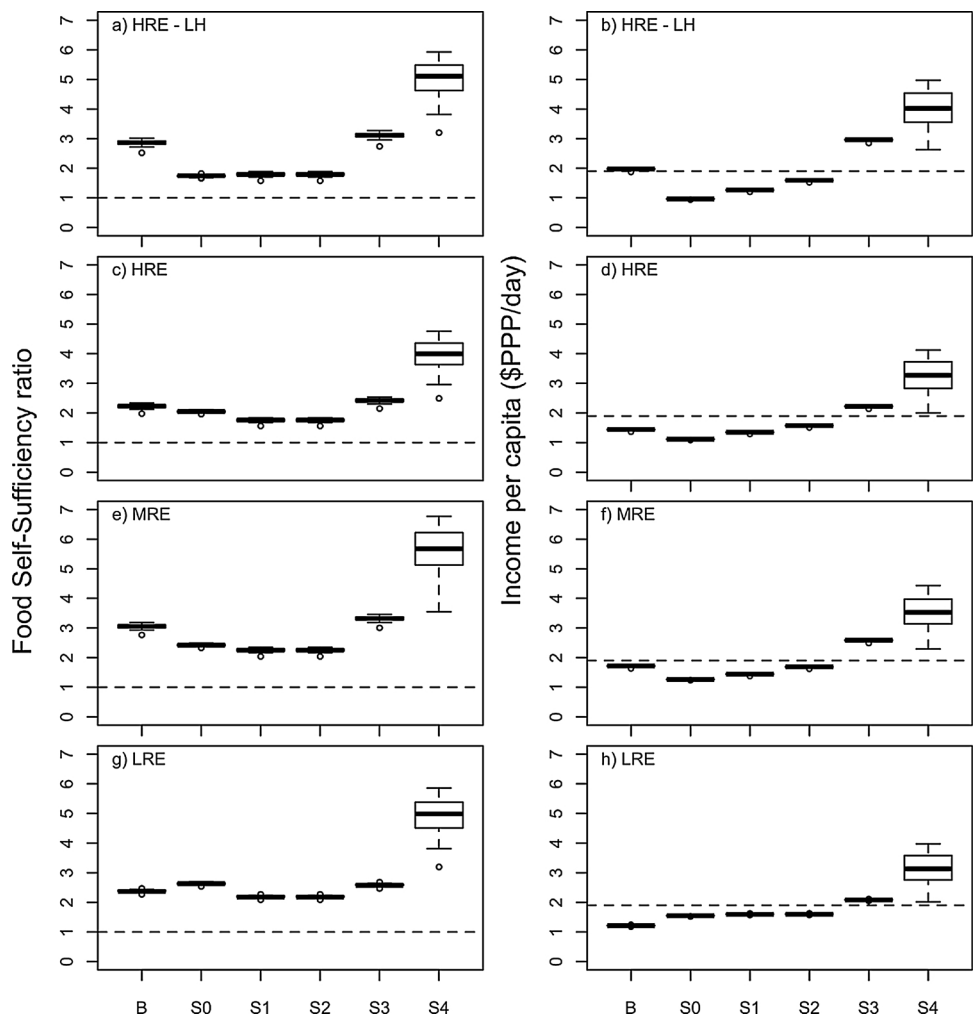


Fig. 3. Boxplots showing food self-sufficiency and farm income per capita averaged for High Resource Endowed with Large Herds (a,b), High Resource Endowed (c,d), Medium Resource Endowed (e,f), and Low Resource Endowed (g,h) farms in 2013 for the baseline (B) and in 2027 for five scenarios of agricultural intensification and policy intervention (S0–S4). The horizontal dotted line is the food self-sufficiency threshold (a,c,e,g) and the poverty line threshold of 1.25 \$PPP/day (b,d,f,h). A detailed description of the scenarios (S0–S4) can be found in Fig. 2 and Table 1. The horizontal line in the box indicates the median for 29 rainfall seasons. The height of the box represents the interquartile range. The whiskers extend to the most extreme data point which is no more than 1.5 times the interquartile range from the edge of the box.

3.7. Sensitivity analysis

Variations in the default trends in rural-urban migration, net fertility rate and cotton price led to large changes in the simulated

percentage of farms that were food self-sufficient and non-poor in 2027 (Fig. 5). For example, the default decrease in net fertility was 35% in the policy interventions with family planning (P3 and P4, from 3.4% to 2.2%, see Table 2). For a +50% deviation from this default trend (from

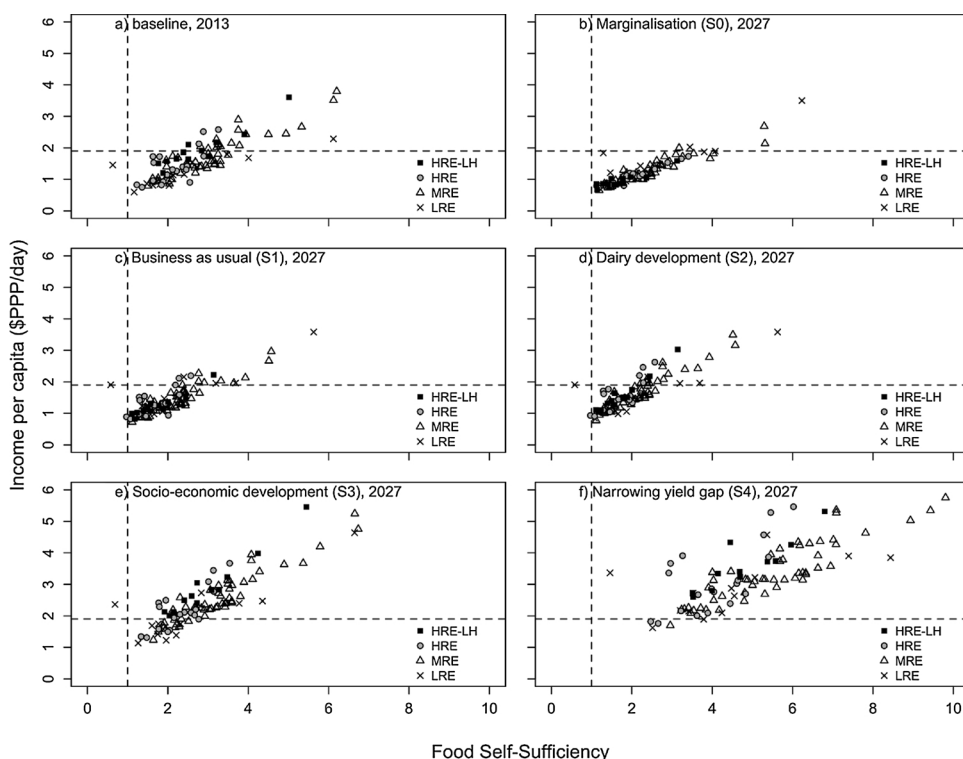


Fig. 4. Food self-sufficiency ratio and income per capita of the 99 households of Namposela village in 2013 (a) and 2027 for different scenarios of agricultural intensification and policy intervention (b, c, d, e, f) for an average rainfall year (734 mm). The horizontal and vertical dotted lines represent the 1.25 \$PPP/day poverty line and the food self-sufficiency threshold respectively.

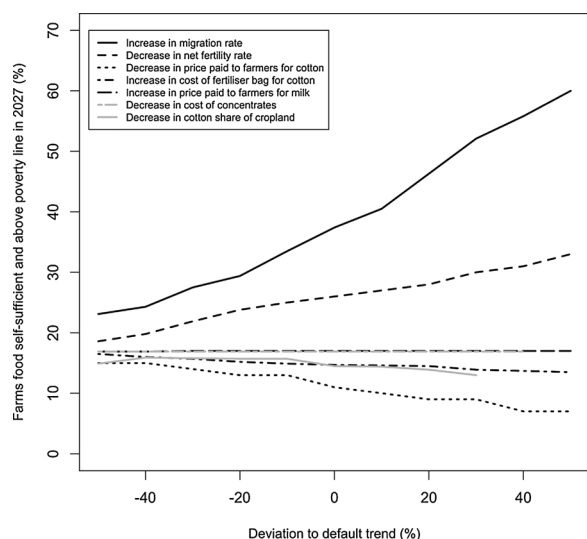


Fig. 5. Percent farms food self-sufficient and above poverty line in 2027 for $\pm 50\%$ variation in the default trend in the key variables constituting five scenarios of agricultural intensification and policy interventions.

3.4% to 1.6%) and all other variables kept to their “no change” value (see Table 2), the simulated percentage of farms food self-sufficient and non-poor in 2027 increased from 26% to 33% (i.e. a 7% percentage point increase). Variation to the default trend of the other variables impacted only marginally the final output of the model framework (Fig. 5).

A decrease in cereal yield due to temperature increase would lead to a 2% percentage point decrease in the percentage of farms food self-sufficient and non-poor in 2027 in S0, and 8% in S1, S2 and S3 scenarios (Table S3).

4. Discussion

4.1. Change in food self-sufficiency and income differed per farm type

Differing migration rates between farm types led to different changes in food self-sufficiency and income per capita (Fig. 3). This factor was overriding differences in farm livestock holdings, practices and yields.

Out-migration in search of remunerative activities is a major element of survival strategies in West Africa (Painter et al., 1994). Our estimate of rural to urban migration rates during the 1994–2010 period for farms in the old cotton basin (from 0 to 2.8% depending on farm type) is in line with the 2% rate reported by de Brauw et al. (2014) for Mali. In an additional survey carried out in 2012, SEP farmers explained that household members migrated to Malian, African, or European cities (73, 27 and 3% of the farms respectively). This low percentage of people migrating to Europe from the Koutiala region explains why remittances are fairly low (180 \$PPP per migrant per year) in the Koutiala region, compared with the Diema region for example which is known for having a high emigration to European countries (remittance of 1233 \$PPP per year per migrant) (Losh et al., 2011). Usually, migration is a result of the difference between the expected return to labour in the home and the potential destination area (Harris and Todaro, 1970; Jayne et al., 2014). Logically, the farms with the lowest labour productivity, i.e. the HRE and LRE farms (Falconnier et al., 2015), experienced the highest migration rate in the 1994–2010 period (see Section 3.1). In the “Business as usual” (S1) scenario, higher out-migration relieved some of the pressure on land and provided more remittances for HRE and LRE farms who therefore suffered from a smaller decrease in food self-sufficiency and income per capita compared with HRE-LH and MRE farms (Fig. 3). Similarly in the “Dairy development” (S2) scenario, HRE farms experienced an increase in income per capita while it decreased for HRE-LH farms although the latter farm type had more cattle and therefore more potential to benefit from improvements in the milk sector. In HRE-LH farms without out-

migration, population growth outpaced the benefits associated with diversification with legume and intensification of livestock production. It was only when out-migration was stimulated by job creation in the cities and rural towns (S3), that the benefits of dairy development could be seen for HRE-LH farms (Fig. 3a and b). Interestingly, though they owned less livestock than HRE and HRE-LH farms, MRE farms also benefited from dairy development because they were able to sell surplus cowpea fodder (Fig. 3f). LRE farms had low income per capita in the baseline, due to their small cotton area and yield. Population growth had very little impact on these small farms given their high rate of out-migration. They owned a very small number of cattle (Falconnier et al., 2015) and therefore didn't benefit from interventions in the milk sector. As a consequence, they remained "hanging in" with low income per capita in the scenarios S0 to S2 (Fig. 3h).

Out-migration could have a detrimental effect on yield due to labour loss. However, in the S3 and S4 scenarios, where the increase in population density is counteracted by family planning and out-migration measures, the latter just offset rather than outpaced population growth. As a result, the number of people in the household in 2027 was similar to the number of people in the baseline year (see Fig. S1) so that no labour shortage had to be expected. Falconnier et al. (2017) showed that with actual household size and cropland area, there is no human labour shortage for cropping activities; the shortage is rather in the availability of oxen. If higher out-migration rates had to be considered in other studies, leading to lower number of people compared with the baseline, an effect of labour loss on yield could be introduced in the modelling framework. The ratio "available labour/required labour" (for crop operations) could be applied to decrease crop yields in the case of insufficient labour.

4.2. Pathways out of poverty?

The marginalisation scenario (S0) strongly resembled the experience of farmers during the period of instability in the cotton sector (2004–2010) (Nubukpo, 2011). The partial replacement of cotton by sorghum, allowed LRE farms to improve their food self-sufficiency status (Fig. 3c and g), but also increased poverty rates in the case of HRE farms (Fig. 4b). The sensitivity analysis indicated that the increase in poverty rates could be amplified if cotton prices paid to farmers would decrease more strongly. Overall, this stresses the crucial role of a well-functioning cotton sector for poverty alleviation in the region (Djouara et al., 2005).

Dairy development is usually considered unlikely in land-constrained environments, due to the strong competition of forage production with existing cash or food crops (De Ridder et al., 2015; Herrero et al., 2014). However, in the "Dairy development" (S2) scenario, the decrease in food self-sufficiency was due to demographic growth, and not to trade-offs between food and fodder production. This was achieved by intercropping cowpea with maize after cotton in the rotation, a niche that guarantees no penalty to maize production (Falconnier et al., 2016). To achieve this type of scenario in reality, an integrative "innovation system" is required where farmers have more political control over the agricultural sector and the policies affecting it (Röling, 2009). Diversification with legume and intensification of livestock production need to be supported by a more favourable milk input/output price ratio, the envisaged outcome of lobbying activities against tariffs for milk imports (Laroche Dupraz and Postolle, 2013). Farmers' policy influence in southern Mali is still weak compared with farmers in France, The Netherlands or the United States for example (Röling, 2009). However, the example of the Agricultural Producers' Organisations of West Africa (ROPPA) regrouping 50 millions farmers across West Africa and defending the right for African states to develop agricultural policies against dumping from Europe (Laroche Dupraz and Postolle, 2013) provides hope that this is not unrealistic.

When dairy development is coupled with socio-economic development and price interventions in the milk sector (S3), a significant

proportion of the village is lifted out of poverty (Fig. 4e). Our study adds to the body of literature showing that out-migration can relieve land pressure and improve livelihoods by pulling rural labour out of agriculture and providing remittances (Beegle et al., 2010; de Brauw et al., 2014). The sensitivity analysis indicated that the livelihood improvement could be strengthened with higher out-migration rates. Rural to urban migration however encompasses a diversity of realities and can be the expression of either "unskilled rural labour being pushed out of agriculture" or educated people "pulled into productive non-farm jobs" (Jayne et al., 2014). There is evidence across sub-Saharan Africa that rural to urban migration can be a "pull" into productive non-farm jobs: in Ethiopia, successful industrial development led to the substitution of shoes imported from China by locally manufactured leather shoes (Sonobe et al., 2009). With a more favourable industrial environment, Mali could develop its textile industry and become a competitive exporter (Cockburn et al., 1999). More generally, Fine et al. (2012) estimated that 122 million young people will get into the labour market in Africa between 2010 and 2020. In an optimistic scenario, they projected that Africa could create only 70 million wage-paying jobs, mainly in manufacturing, government and service sectors. The size of the labour force therefore appears to be growing faster than economies can create job opportunities (Fox and Sohnesen, 2012) and agriculture will still have an important role to play in poverty reduction.

Family planning exerted the same influence as out-migration and allowed improving farmers' livelihood. In Mali, demographic surveys indicated that 28% of the women expressed an unmet demand for contraception (Population Council and ICF International, 2015), showing the scope for a change in reproductive behaviour and the need for stronger political commitment to family planning. Husband's disapproval may however discourage women from taking control of their fertility (Barnett et al., 1999) and a broader change in social and gender norms would therefore be needed. Raising the female education level would allow increasing women potential earnings and bargaining power in the household, which can contribute to reduce fertility rates (Canning et al., 2015). In Kenya, a 30% reduction in net fertility rate (from 3.7 to 2.8%) was achieved within a 15 years timespan (1980–1995) (World Bank, <http://data.worldbank.org/indicator/SP.DYN.CBRT.IN>, last accessed 29/09/2016), indicating that the decrease in net fertility rates considered in our simulation (–35%) would be achievable if appropriate measures were taken. A stronger reduction in net fertility rates could further improve poverty reduction (Fig. 5).

When added to the previous interventions and change in practices, narrowing the yield gap allowed a massive increase in food self-sufficiency (Fig. 3) and lifted almost the totality of the village out of poverty (Fig. 4f). However, at the same time, it increased the variability of food self-sufficiency and income, because of increased crop sensitivity to rainfall when nutrient limitation is alleviated (Affholder, 1995; Ripoché et al., 2015). In 'bad' seasons, small yields would push some HRE farms close to the poverty line (Fig. 4h). This risk of unfavourable cost:benefit ratios is common in the context of sub-Saharan Africa (Bielders and Gérard, 2015; Ronner et al., 2016) and could impede the adoption of higher fertilizer application rates. As yields have been stagnant in the past 20 years (Falconnier et al., 2015), this scenario of narrowing the yield gap in only 15 years is very ambitious. Moreover, it is questionable from a sustainability point of view, because extensive subsidy programs put a heavy load on public agricultural investments and potentially remove finances from other areas of agricultural development (Marenja et al., 2012).

Due to increased temperatures, climate change is expected to have adverse effects on crop yields (Sultan et al., 2013). Our analysis showed that this would negatively affect income per capita and significantly reduce the percentage of farms non-poor and self-sufficient, hence highlighting the vulnerability of the smallholder population. Adaptation to climate change is thus a key aspect of policy making that should start today in order to be ready for a warmer future. Effective policy making should support the co-design of adaptation options with all

stakeholders including farmers and researchers (e.g. adoption of improved/adapted varieties and adjustment of planting times and fertilization) (Guan et al., 2017; Traore et al., 2017). Furthermore, progressive institutional arrangements such as the development of insurance schemes, weather forecasting, and early warning systems will be key to encourage the adoption of these adaptation strategies. Other transformative measures, e.g. building the capacity of farmers to diversify cropping systems, improve market functioning and value chains development should also be a priority (Descheemaeker et al., 2016).

The case study village is representative for other sites with similar agro-ecological and socio-institutional factors (cotton/cereal rotations and variable rainfall, high population pressure, credit for inputs and guaranteed purchase of cotton). The pathways out of poverty identified here therefore hold for the broad “old cotton basin” that accommodates more than a million of rural people. Finally, our analysis indicates that none of the tested policy interventions and agriculture intensification strategies alone can lift an entire heterogeneous farm population out of poverty (Fig. 4). It is rather the strategic combination of different multi-sectoral interventions that may offer a solution for poverty alleviation. This key finding adds to the increasing recognition that understanding the future of agriculture requires to move from a singular focus on agricultural interventions to a more holistic and multisectoral analysis (Frelat et al., 2016; Thompson and Scoones, 2009).

5. Conclusion

Five scenarios combining incremental policy interventions and agricultural intensification were explored for a village of 99 households in the ‘old cotton basin’ in Southern Mali. For land-constrained areas like the study region, differential rural-urban migration rates appeared to be a key factor in understanding the different responses of the farms types. To guarantee food self-sufficiency and poverty reduction in the case of a variable climate, the creation of wage jobs to allow people to move out of agriculture and family planning to reduce human fertility rates should complement agricultural intensification interventions. Our study showed that, along with changes in farmer practices towards intensification, several incremental policy interventions in different sectors are needed to lift the entire farm population above the poverty line. This calls for a holistic and multisectoral assessment of plausible futures when trying to reduce rural poverty in land constrained Africa.

Acknowledgements

Funding for this research was provided by the McKnight Foundation (N° 12-112 and 12-634) through the project ‘Pathways to Agro-ecological Intensification of Sorghum and Millet Cropping Systems of Southern Mali’. We thank the Institut d’Economie Rurale (IER) and Cirad for making available the SEP panel dataset and the N°Tarla long-term experiment dataset. We are grateful to the CMDT who made available the Nampossela household survey. We thank André Nenkam and Folorunso Akinseye for making available APSIM calibrations for maize, sorghum and millet. We thank the AgMIP research community for their contributions to the crop modelling activities and the United Kingdom Department for International Development for their support of AgMIP.

Appendix A. Supplementary data

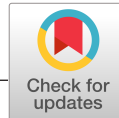
Supplementary data associated with this article can be found, in the online version, at <http://dx.doi.org/10.1016/j.landusepol.2017.10.044>.

References

Affholder, F., 1995. Effect of organic matter input on the water balance and yield of millet under tropical dryland condition. *Field Crops Res.* 41, 109–121. [http://dx.doi.org/10.1016/0378-4290\(94\)00115-5](http://dx.doi.org/10.1016/0378-4290(94)00115-5).

- African Development Bank, 2012. African Economic Outlook 2012. Special Theme: Promoting Youth Employment. OECD Publishing. http://www.oecd-ilibrary.org/fr/development/african-economic-outlook-2012_aeo-2012-en.
- Aparisi, A.M., Diallo, F., Badié, J., 2012. Analyse des incitations et pénalisations pour le lait au Mali. FAO, Rome. <http://www.fao.org/3/a-at572f.pdf>.
- Ba, A., Lesnoff, M., Pocard-Chapuis, R., Moulin, C.-H., 2011. Demographic dynamics and off-take of cattle herds in southern Mali. *Trop. Anim. Health Prod.* 43, 1101–1109. <http://dx.doi.org/10.1007/s11250-011-9808-2>.
- Barnett, B., Konaté, M., Mhloyi, M., Mutambirwa, J., Francis-Chizororo, M., Taruberekera, N., Ulin, P., Konate, M., 1999. The impact of family planning on women's lives: findings from the women's studies project in Mali and Zimbabwe. *Afr. J. Reprod. Health* 3, 27. <http://dx.doi.org/10.2307/3583226>.
- Baudron, F., Sims, B., Justice, S., Kahan, D.G., Rose, R., Mkomwa, S., Kaumbutho, P., Sariah, J., Nazare, R., Moges, G., Gérard, B., 2015. Re-examining appropriate mechanization in Eastern and Southern Africa: two-wheel tractors, conservation agriculture, and private sector involvement. *Food Secur.* 7, 889–904. <http://dx.doi.org/10.1007/s12571-015-0476-3>.
- Beegle, K., De Weerd, J., Dercon, S., 2010. Migration and economic mobility in Tanzania: evidence from a tracking survey. *Rev. Econ. Stat.* 93, 1010–1033. http://dx.doi.org/10.1162/REST_a_00105.
- Benjaminsen, T.A., Aune, J.B., Sidibé, D., 2010. A critical political ecology of cotton and soil fertility in Mali. *Geoforum* 41, 647–656. <http://dx.doi.org/10.1016/j.geoforum.2010.03.003>.
- Bielders, C.L., Gérard, B., 2015. Millet response to microdose fertilization in South-Western Niger: effect of antecedent fertility management and environmental factors. *Field Crops Res.* 171, 165–175. <http://dx.doi.org/10.1016/j.fcr.2014.10.008>.
- Bizikova, L., Pintér, L., Tubiello, N., 2015. Normative scenario approach: a vehicle to connect adaptation planning and development needs in developing countries. *Reg. Environ. Change* 15, 1433–1446. <http://dx.doi.org/10.1007/s10113-014-0705-x>.
- Bongaarts, J., 2011. Can family planning programs reduce high desired family size in Sub-Saharan Africa? *Int. Perspect. Sexual Reprod. Health* 37, 209–216. <http://dx.doi.org/10.1363/3720911>.
- Britten, P., Marcoe, K., Yamini, S., Davis, C., 2006. Development of food intake patterns for the MyPyramid Food Guidance System. *J. Nutr. Educ. Behav.* 38, S78–S92.
- Canning, D., Raja, S., Yazbeck, A.S. (Eds.), 2015. Africa's Demographic Transition: Dividend or Disaster? The World Bank. <http://dx.doi.org/10.1596/978-1-4648-0489-2>.
- Cockburn, J., Siggel, E., Coulbaly, M., Vézina, S., 1999. Measuring competitiveness and its sources: the case of Mali's manufacturing sector. *Can. J. Dev. Stud.* 20, 491–519. <http://dx.doi.org/10.1080/02255189.1999.9669852>.
- Corniaux, C., Vatin, F., Ancy, V., 2012. Lait en poudre importé versus production locale en Afrique de l'Ouest: vers un nouveau modèle industriel? *Cahiers Agric.* 21, 18–24. <http://dx.doi.org/10.1684/agr.2012.0536>.
- Coulbaly, J.Y., Sanders, J.H., Preckel, P.V., Baker, T.G., 2015. Will cotton make a comeback in Mali? *Agric. Econ.* 46, 53–67. <http://dx.doi.org/10.1111/agec.12140>.
- Coulbaly, A., 2003. Country Pasture and Forage Resources Profiles. FAO, Rome. <http://www.fao.org/ag/agp/agpc/doc/counprof/PDF%20files/Mali-English.pdf>.
- de Brauw, A., Mueller, V., Lee, H.L., 2014. The role of rural-urban migration in the structural transformation of Sub-Saharan Africa. *World Dev. Econ. Transform. Afr.* 63, 33–42. <http://dx.doi.org/10.1016/j.worlddev.2013.10.013>.
- de la Croix, K., Marie, J., Ferry, L., Landy, F., 2011. New dynamics of farming mechanization: trade, uses and spatialization in the Ségou region (Mali). *Ann. Geogr. Nubukpo* 174–192.
- De Ridder, N., Sanogo, O.M., Rufino, M.C., van Keulen, H., Giller, K.E., 2015. Milk: the new white gold? Milk production options for smallholder farmers in Southern Mali. *Animal* 1–9. <http://dx.doi.org/10.1017/S175173115000178>.
- Descheemaeker, K., Oosting, S.J., Homann-Kee Tui, S., Masikati, P., Falconnier, G.N., Giller, K.E., 2016. Climate change adaptation and mitigation in smallholder crop-livestock systems in Sub-Saharan Africa: a call for integrated impact assessments. *Reg. Environ. Change* 16, 2331–2343. <http://dx.doi.org/10.1007/s10113-016-0957-8>.
- Djouara, H., Belières, J.F., Kébé, D., 2005. Les exploitations agricoles familiales de la zone cotonnière du mali face à la baisse des prix du coton graine. *Cahiers Agric.* 15, 64–71.
- Dorward, A., Chirwa, E., 2011. The Malawi agricultural input subsidy programme: 2005/06 to 2008/09. *Int. J. Agric. Sustainability* 9, 232–247. <http://dx.doi.org/10.3763/ijas.2010.0567>.
- Enfors, E.I., Gordon, L.J., Peterson, G.D., Bossio, D., 2008. Making investments in dryland development work: participatory scenario planning in the Makanya catchment, Tanzania. *Ecol. Soc.* 13, 42.
- FAO, 2006. Guidelines for Soil Description. Food & Agriculture Organization of the United Nations, Rome.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Sanogo, O.M., Giller, K.E., 2015. Understanding farm trajectories and development pathways: two decades of change in southern Mali. *Agric. Syst.* 139, 210–222. <http://dx.doi.org/10.1016/j.agsy.2015.07.005>.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. *Field Crops Res.* 187, 113–126. <http://dx.doi.org/10.1016/j.fcr.2015.12.015>.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K.E., 2017. Co-learning cycles to support the design of innovative farm systems in southern Mali. *Eur. J. Agron.* 89, 61–74. <http://dx.doi.org/10.1016/j.eja.2017.06.008>.
- Fine, D., van Wamelen, A., Lund, S., Cabral, A., Taoufik, M., Dörr, N., Leke, A., Roxburgh, C., Schubert, J., Cook, P., 2012. Africa at Work: Job Creation and Inclusive Growth.

- McKinsey Global Institute, Boston.
- Fox, L., Sohnesen, T.P., 2012. Household Enterprises in Sub-Saharan Africa: Why They Matter for Growth, Jobs, and Livelihoods. World Bank, Washington, D.C. <http://www.afdb.org/fileadmin/uploads/afdb/Documents/Knowledge/Household%20Enterprise%20in%20Sub-Saharan%20Africa%20-%20Why%20they%20Matter%20for%20Growth%20Jobs%20and%20Livelihoods.pdf>.
- Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., Rigolot, C., Ritzema, R.S., Rodriguez, D., van Asten, P.J.A., van Wijk, M.T., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proc. Natl. Acad. Sci. U. S. A.* 113, 458–463. <http://dx.doi.org/10.1073/pnas.1518384112>.
- García-Martínez, A., Bernués, A., Olaizola, A.M., 2011. Simulation of mountain cattle farming system changes under diverse agricultural policies and off-farm labour scenarios. *Livestock Sci.* 137, 73–86. <http://dx.doi.org/10.1016/j.livsci.2010.10.002>.
- Gibrel, T.M., Herrmann, S., Berkhoff, K., Nuppenau, E.-A., Rinn, A., 2014. Farm types as an interface between an agroecological model and CLUE-Naban land change model: application for scenario modelling. *Ecol. Indic.* 36, 766–778. <http://dx.doi.org/10.1016/j.ecolind.2013.09.009>.
- Guan, K., Sultan, B., Biasutti, M., Baron, C., Lobell, D.B., 2017. Assessing climate adaptation options and uncertainties for cereal systems in West Africa. *Agric. For. Meteorol.* 232, 291–305. <http://dx.doi.org/10.1016/j.agrformet.2016.07.021>.
- Harris, D., Orr, A., 2014. Is rainfed agriculture really a pathway from poverty? *Agric. Syst.* 123, 84–96. <http://dx.doi.org/10.1016/j.agry.2013.09.005>.
- Harris, J.R., Todaro, M.P., 1970. Migration, unemployment and development: a two-sector analysis. *Am. Econ. Rev.* 60, 126–142.
- Headey, D.D., Jayne, T.S., 2014. Adaptation to land constraints: is Africa different? *Food Policy* 48, 18–33. <http://dx.doi.org/10.1016/j.foodpol.2014.05.005>.
- Herrero, M., Thornton, P.K., Bernués, A., Baltenweck, I., Vervoort, J., van de Steeg, J., Makokha, S., van Wijk, M.T., Karanja, S., Rufino, M.C., Staal, S.J., 2014. Exploring future changes in smallholder farming systems by linking socio-economic scenarios with regional and household models. *Global Environ. Change* 24, 165–182. <http://dx.doi.org/10.1016/j.gloenvcha.2013.12.008>.
- Hillocks, R.J., 2014. Addressing the yield gap in Sub-Saharan Africa. *Outlook Agric.* 43, 85–90. <http://dx.doi.org/10.5367/oa.2014.0163>.
- Jayne, T.S., Chamberlin, J., Headey, D.D., 2014. Land pressures, the evolution of farming systems, and development strategies in Africa: a synthesis. *Food Policy* 48, 1–17. <http://dx.doi.org/10.1016/j.foodpol.2014.05.014>.
- Jolliffe, D., Prydz, E.B., 2016. Estimating international poverty lines from comparable national thresholds. *J. Econ. Inequal.* 14, 185–198. <http://dx.doi.org/10.1007/s10888-016-9327-5>.
- Jonckers, D., Colley, J.-P., 1974. La communauté familiale chez les Minyanka du Mali. *J. Soc. Africaines* 44, 43–52. <http://dx.doi.org/10.3406/jafr.1974.1748>.
- Keating, B.A., Carberry, P.S., Hammer, G.L., Probert, M.E., Robertson, M.J., Holzworth, D., Huth, N.I., Hargreaves, J.N.G., Meinke, H., Hochman, Z., McLean, G., Verburg, K., Snow, V., Dimes, J.P., Silburn, M., Wang, E., Brown, S., Bristow, K.L., Asseng, S., Chapman, S., McCown, R.L., Freebairn, D.M., Smith, C.J., 2003. An overview of APSIM, a model designed for farming systems simulation. *Eur. J. Agron.* 18, 267–288. [http://dx.doi.org/10.1016/S1161-0301\(02\)00108-9](http://dx.doi.org/10.1016/S1161-0301(02)00108-9).
- Kelly, V., Perakis, S., Diallo, B., Dembélé, N.N., 2010. Cottonseed, Oil, and Cake: Co-Products or By-Products in the C-4 Cotton Sectors? Michigan State University, East Lansing. http://www.fsg.afre.msu.edu/cotton/English_Cottonseed_April2011.pdf.
- Kelly, V., Boughton, D., Magen, B., 2011. Cereal Market Dynamics: The Malian Experience from the 1990 to Present. MSU International Development Working Paper.
- Laroche Dupraz, C., Postolle, A., 2013. Food sovereignty and agricultural trade policy commitments: how much leeway do West African nations have? *Food Policy* 38, 115–125. <http://dx.doi.org/10.1016/j.foodpol.2012.11.005>.
- Losh, B., Fréguin-Gresh, S., White, E., 2011. Rural Transformation and Late Developing Countries in a Globalizing World. A Comparative Analysis of Rural Change. Final Report of the RuralStruc Program, Revised Version. World Bank, Washington, DC. http://siteresources.worldbank.org/AFRICAEXT/Resources/258643-1323805221801/RuralStruc_final_report_v2_hd.pdf.
- Marennya, P., Nkonya, E., Xiong, W., Deustua, J., Kato, E., 2012. Which policy would work better for improved soil fertility management in sub-Saharan Africa, fertilizer subsidies or carbon credits? *Agric. Syst.* 110, 162–172. <http://dx.doi.org/10.1016/j.agry.2012.04.004>.
- Miguel Ayala, L., van Eupen, M., Zhang, G., Pérez-Soba, M., Martorano, L.G., Lisboa, L.S., Beltrao, N.E., 2016. Impact of agricultural expansion on water footprint in the Amazon under climate change scenarios. *Sci. Total Environ.* 569, 1159–1173. <http://dx.doi.org/10.1016/j.scitotenv.2016.06.191>.
- Ministère de la santé et de l'hygiène publique, 2014. Plan d'action national de planification familiale du mali 2014-2018. République du Mali. République du Mali (<http://ec2-54-210-230-186.compute-1.amazonaws.com/wp-content/uploads/2016/05/Plan-PF-Mali.pdf>).
- Nubukpo, K., 2011. L'économie politique de la réforme des filières cotonnières d'Afrique de l'Ouest et du centre: vers la convergence des modes d'organisation? *Mondes dév* 155, 93–109. <http://dx.doi.org/10.3917/med.155.0093>.
- O'Neill, B.C., Krieger, E., Ebi, K.L., Kemp-Benedict, E., Riahi, K., Rothman, D.S., van Ruijven, B.J., van Vuuren, D.P., Birkmann, J., Kok, K., Levy, M., Solecki, W., 2017. The roads ahead: Narratives for shared socioeconomic pathways describing world futures in the 21st century. *Glob. Environ. Change* 42, 169–180. <http://dx.doi.org/10.1016/j.gloenvcha.2015.01.004>.
- Pachauri, R.K., Mayer, L., 2015. Climate Change 2014: Synthesis Report. In: Intergovernmental Panel on Climate Change (Ed.), Intergovernmental Panel on Climate Change, Geneva, Switzerland.
- Painter, T., Sumberg, J., Price, T., 1994. Your terroir and my 'action space': implications of differentiation, mobility and diversification for the approche terroir in Sahelian West Africa. *Africa* 64, 447. <http://dx.doi.org/10.2307/1161368>.
- Paul, B.K., Frelat, R., Birnholz, C., Ebong, C., Gahigi, A., Groot, J.C.J., Herrero, M., Kagabo, D.M., Notenbaert, A., Vanlauwe, B., van Wijk, M.T., 2017. Agricultural intensification scenarios, household food availability and greenhouse gas emissions in Rwanda: ex-ante impacts and trade-offs. *Agric. Syst.* <http://dx.doi.org/10.1016/j.agry.2017.02.007>. (in press).
- Poccard-Chapuis, R., Coulibaly, D., Ba, A., Sissoko, S., Bengaly, M., Coulibaly, J., 2007. Analyse Affinée des Pratiques et des Stratégies Paysannes, Rapport technique, Activité 3, PASE-1. IER, Sikasso, Mali.
- Population Council, ICF International, 2015. Mali 2012-13 DHS. *Stud. Fam. Plann.* 46, 227–236. <http://dx.doi.org/10.1111/j.1728-4465.2015.00026.x>.
- Röling, N., 2009. Pathways for impact: scientists' different perspectives on agricultural innovation. *Int. J. Agric. Sustainability* 7, 83–94. <http://dx.doi.org/10.3763/ijas.2009.0043>.
- Rajib, M.A., Abiablame, L., Paul, M., 2016. Modeling the effects of future land use change on water quality under multiple scenarios: a case study of low-input agriculture with hay/pasture production. *Sustainability Water Qual. Ecol.* 8, 50–66. <http://dx.doi.org/10.1016/j.swaqe.2016.09.001>.
- Ravallion, M., Chen, S., Sangraula, P., 2009. Dollar a day revisited. *World Bank Econ. Rev.* 23, 163–184. <http://dx.doi.org/10.1093/wber/lhp007>.
- Ripoche, A., Crétenet, M., Corbeels, M., Affholder, F., Naudin, K., Sissoko, F., Douzet, J.-M., Titttonell, P., 2015. Cotton as an entry point for soil fertility maintenance and food crop productivity in savannah agroecosystems: evidence from a long-term experiment in southern Mali. *Field Crops Res.* 177, 37–48. <http://dx.doi.org/10.1016/j.fcr.2015.02.013>.
- Ritzema, R.S., Frelat, R., Douchamps, S., Silvestri, S., Rufino, M.C., Herrero, M., Giller, K.E., Lopez-Ridaura, S., Teufel, N., Paul, B.K., Wijk van, M.T., 2017. Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from East and West Africa. *Food Sec.* 9, 115–131. <http://dx.doi.org/10.1007/s12571-016-0638-y>.
- Ronner, E., Franke, A.C., Vanlauwe, B., Dianda, M., Edeh, E., Ukem, B., Bala, A., van Heerwaarden, J., Giller, K.E., 2016. Understanding variability in soybean yield and response to P-fertilizer and rhizobium inoculants on farmers' fields in northern Nigeria. *Field Crops Res.* 186, 133–145. <http://dx.doi.org/10.1016/j.fcr.2015.10.023>.
- Samake, A., Belières, J.F., Corniaux, C., Dembele, N., Kelly, V., Marzin, J., Sanogo, O., Staat, J., 2008. Changements structurels des économies rurales dans la mondialisation. Programme RuralStruc Mali – Phase I. World Bank, Washington, DC. http://siteresources.worldbank.org/AFRICAEXT/Resources/RURALSTRUC-MALI_Phase2.pdf.
- Silvie, P.J., Renou, A., Vodounnon, S., Bonni, G., Adegnika, M.O., Héma, O., Prudent, P., Sorèze, J., Ochou, G.O., Togola, M., Badiane, D., Ndour, A., Akantetou, P.K., Ayea, B., Brévault, T., 2013. Threshold-based interventions for cotton pest control in West Africa: what's up 10 years later? *Crop Prot.* 43, 157–165. <http://dx.doi.org/10.1016/j.cropro.2012.09.006>.
- Sonobe, T., Akoten, J.E., Otsuka, K., 2009. An exploration into the successful development of the leather-shoe industry in Ethiopia. *Rev. Dev. Econ.* 13, 719–736. <http://dx.doi.org/10.1111/j.1467-9361.2009.00526.x>.
- Soumaré, M., Bazile, D., Kouressy, M., Diallo, K., Diakité, C.H., 2008. Diversité agroécologique et devenir des céréales traditionnelles au sud du Mali. *Cahiers Agric.* 17, 79–85.
- Stephenné, N., Lambin, E.F., 2004. Scenarios of land-use change in Sudano-sahelian countries of Africa to better understand driving forces. *Geo J.* 61, 365–379.
- Sultan, B., Roudier, P., Quirion, P., Alhassane, A., Muller, B., Dingkuhn, M., Ciaï, P., Guimberteau, M., Traore, S., Baron, C., 2013. Assessing climate change impacts on sorghum and millet yields in the Sudanian and Sahelian savannas of West Africa. *Environ. Res. Lett.* 8, 014040. <http://dx.doi.org/10.1088/1748-9326/8/1/014040>.
- Thompson, J., Scoones, I., 2009. Addressing the dynamics of agri-food systems: an emerging agenda for social science research. *Environ. Sci. Policy* 12, 386–397. <http://dx.doi.org/10.1016/j.envsci.2009.03.001>.
- Traore, S., Doumbia, A., Traore, V., Tolno, D., 2011. 4ème Recensement General De La Population Et De l'habitat Du Mali (Rgph-2009). INSTAT, Bamako, Mali. http://www.unfpa-mali.org/sites/default/files/Rapport_Etat_Structure_Version%2022%20Dec%202011.pdf.
- Traore, B., Corbeels, M., van Wijk, M.T., Rufino, M.C., Giller, K.E., 2013. Effects of climate variability and climate change on crop production in southern Mali. *Eur. J. Agron.* 49, 115–125. <http://dx.doi.org/10.1016/j.eja.2013.04.004>.
- Traore, B., Van Wijk, M.T., Descheemaeker, K., Corbeels, M., Rufino, M.C., Giller, K.E., 2015. Climate variability and change in southern Mali: learning from farmer perceptions and on-farm trials. *Exp. Agric.* 51, 615–634. <http://dx.doi.org/10.1017/S0014479714000507>.
- Traore, B., Descheemaeker, K., van Wijk, M.T., Corbeels, M., Supit, I., Giller, K.E., 2017. Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. *Field Crops Res.* 201, 133–145. <http://dx.doi.org/10.1016/j.fcr.2016.11.002>.
- Traore, B., 2014. Climate Change, Climate Variability and Adaptation Options in Smallholder Cropping Systems of the Sudano – Sahel Region in West Africa. PhD Thesis. Wageningen University, Wageningen.
- United Nations, 2015. World Population Prospects. Volume I: Comprehensive Tables. United Nations, New York. http://esa.un.org/unpd/wpp/Publications/Files/WPP2015_Volume-I_Comprehensive-Tables.pdf.
- van Ittersum, M.K., Cassman, K.G., Grassini, P., Wolf, J., Titttonell, P., Hochman, Z., 2013. Yield gap analysis with local to global relevance—a review. *Field Crops Res.* 143, 4–17. <http://dx.doi.org/10.1016/j.fcr.2012.09.009>.



Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa

Gatien N. Falconnier¹ | Marc Corbeels^{1,2} | Kenneth J. Boote³ | François Affholder¹ | Myriam Adam^{4,5} | Dilys S. MacCarthy⁶ | Alex C. Ruane⁷ | Claas Nendel⁸ | Anthony M. Whitbread⁹ | Éric Justes¹⁰ | Lajpat R. Ahuja¹¹ | Folorunso M. Akinseye¹² | Isaac N. Alou¹³ | Kokou A. Amouzou¹⁴ | Saseendran S. Anapalli¹⁵ | Christian Baron^{16,17} | Bruno Basso¹⁸ | Frédéric Baudron¹⁹ | Patrick Bertuzzi²⁰ | Andrew J. Challinor²¹ | Yi Chen^{22,23} | Delphine Deryng^{24,25} | Maha L. Elsayed²⁶ | Babacar Faye²⁷ | Thomas Gaiser²⁷ | Marcelo Galdos²¹ | Sebastian Gayler²⁸ | Edward Gerardeaux¹ | Michel Giner¹ | Brian Grant²⁹ | Gerrit Hoogenboom³ | Esther S. Ibrahim⁸ | Bahareh Kamali⁸ | Kurt Christian Kersebaum⁸ | Soo-Hyung Kim³⁰ | Michael van der Laan¹³ | Louise Leroux^{1,31} | Jon I. Lizaso³² | Bernardo Maestrini¹⁸ | Elizabeth A. Meier³³ | Fasil Mequanint²⁸ | Alain Ndoli¹⁹ | Cheryl H. Porter³ | Eckart Priesack³⁴ | Dominique Ripoche²⁰ | Tesfaye S. Sida³⁵ | Upendra Singh³⁶ | Ward N. Smith²⁹ | Amit Srivastava²⁷ | Sumit Sinha²¹ | Fulu Tao^{22,23,37} | Peter J. Thorburn³³ | Dennis Timlin³⁸ | Boubou Traore³⁹ | Tracy Twine⁴⁰ | Heidi Webber⁸

¹AIDA, Univ Montpellier, CIRAD, Montpellier, France²CIMMYT, Nairobi, Kenya³University of Florida, Gainesville, FL, USA⁴CIRAD, UMR AGAP, Bobo-Dioulasso, Burkina Faso⁵AGAP, Univ Montpellier, CIRAD, INRA, Montpellier SupAgro, Montpellier, France⁶Soil and Irrigation Research Centre, School of Agriculture, College of Basic and Applied Science, University of Ghana, Accra, Ghana⁷Climate Impacts Group, National Aeronautics and Space Administration Goddard Institute for Space Studies, New York, NY, USA⁸Leibniz Centre for Agricultural Landscape Research, Müncheberg, Germany⁹International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Dar es Salaam, Tanzania¹⁰PERSYST, Univ Montpellier, CIRAD, Montpellier, France¹¹USDA-ARS, Fort Collins, CO, USA¹²International Crops Research Institute for the Semi-Arid Tropics (ICRISAT), Kano, Nigeria¹³Department of Plant and Soil Sciences, University of Pretoria, Pretoria, South Africa¹⁴West Africa Program, African Plant Nutrition Institute (APNI), Yamoussoukro, Cote d'Ivoire¹⁵Sustainable Water Management Research Unit, USDA-ARS, Stoneville, MS, USA¹⁶CIRAD, UMR TETIS, Montpellier, France¹⁷TETIS, Univ Montpellier, AgroParisTech, CIRAD, CNRS, IRSTEA, Montpellier, France¹⁸Department of Earth and Environmental Sciences, Michigan State University, East Lansing, MI, USA¹⁹CIMMYT, Harare, Zimbabwe²⁰INRA, Agroclim, France

Lajpat R. Ahuja has retired.

²¹Institute for Climate and Atmospheric Science, School of Earth and Environment, University of Leeds, Leeds, UK

²²Key Laboratory of Land Surface Pattern and Simulation, Institute of Geographical Sciences and Natural Resources Research, Chinese Academy of Sciences, Beijing, China

²³College of Resources and Environment, University of Chinese Academy of Sciences, Beijing, China

²⁴Integrative Research Institute on Transformations of Human-Environment Systems (IRI THESys), Humboldt-Universität zu Berlin, Berlin, Germany

²⁵NewClimate Institute, Berlin, Germany

²⁶MALR-ARC, Central Laboratory for Agricultural Climate (CLAC), Giza, Egypt

²⁷Crop Science Group, Institute of Crop Science and Resource Conservation (INRES), University of Bonn, Bonn, Germany

²⁸Institute of Soil Science and Land Evaluation, Biogeophysics, University of Hohenheim, Stuttgart, Germany

²⁹Ottawa Research and Development Centre, Agriculture and Agri-Food Canada, Ottawa, ON, Canada

³⁰School of Environmental and Forest Sciences, University of Washington, Seattle, USA

³¹CIRAD, UPR AIDA, Dakar, Senegal

³²CEIGRAM-Universidad Politécnica de Madrid, ETSIAAB, Madrid, Spain

³³CSIRO Agriculture and Food, Queensland Bioscience Precinct, St Lucia, Qld, Australia

³⁴Institute of Biochemical Plant Pathology, Helmholtz Center Munich, Neuherberg, Germany

³⁵CIMMYT, Addis Ababa, Ethiopia

³⁶International Center for Soil Fertility and Agricultural Development, Muscle Shoals, AL, USA

³⁷Natural Resources Institute Finland (Luke), Helsinki, Finland

³⁸Crop Systems and Global Change Research Unit, USDA-ARS, Beltsville, MD, USA

³⁹IER, Bamako, Mali

⁴⁰Department of Soil, Water, and Climate, University of Minnesota, St. Paul, MN, USA

Correspondence

Gatien N. Falconnier, AIDA, Univ
Montpellier, CIRAD, Montpellier, France.
Email: gatien.falconnier@cirad.fr

Abstract

Smallholder farmers in sub-Saharan Africa (SSA) currently grow rainfed maize with limited inputs including fertilizer. Climate change may exacerbate current production constraints. Crop models can help quantify the potential impact of climate change on maize yields, but a comprehensive multimodel assessment of simulation accuracy and uncertainty in these low-input systems is currently lacking. We evaluated the impact of varying $[\text{CO}_2]$, temperature and rainfall conditions on maize yield, for different nitrogen (N) inputs (0, 80, 160 kg N/ha) for five environments in SSA, including cool subhumid Ethiopia, cool semi-arid Rwanda, hot subhumid Ghana and hot semi-arid Mali and Benin using an ensemble of 25 maize models. Models were calibrated with measured grain yield, plant biomass, plant N, leaf area index, harvest index and in-season soil water content from 2-year experiments in each country to assess their ability to simulate observed yield. Simulated responses to climate change factors were explored and compared between models. Calibrated models reproduced measured grain yield variations well with average relative root mean square error of 26%, although uncertainty in model prediction was substantial ($\text{CV} = 28\%$). Model ensembles gave greater accuracy than any model taken at random. Nitrogen fertilization controlled the response to variations in $[\text{CO}_2]$, temperature and rainfall. Without N fertilizer input, maize (a) benefited less from an increase in atmospheric $[\text{CO}_2]$; (b) was less affected by higher temperature or decreasing rainfall; and (c) was more affected by increased rainfall because N leaching was more critical. The model intercomparison revealed that simulation of daily soil N supply and N leaching plays a crucial role in simulating climate change impacts for low-input systems. Climate change and N input interactions have strong implications for the design of robust adaptation approaches across SSA, because the impact of climate change in low input

systems will be modified if farmers intensify maize production with balanced nutrient management.

KEYWORDS

crop simulation model, ensemble modelling, model intercomparison, smallholder farming systems, uncertainty

1 | INTRODUCTION

Rainfed maize production is crucial for food security and smallholder livelihoods in sub-Saharan Africa (SSA). Maize is the largest contributor to the total value of staple crop production in Western, Eastern, Central and Southern Africa (OCDE & FAO, 2016). With limited access to means of income diversification and safety nets, smallholder farmers in SSA are highly vulnerable to climate change (Connolly-Boutin & Smit, 2016; Descheemaeker et al., 2016). Temperatures are expected to increase in West, East and Southern Africa, with multimodel climate projections indicating a warming of 1–4°C in the decades of 2081–2100 relative to 1986–2005 depending on the representative concentration pathway (RCP) considered (IPCC, 2013). Annual rainfall is expected to increase in West and East Africa (0% to +12% depending on RCP) and to decrease in Southern Africa (–5% to –10% depending on RCP; IPCC, 2013). The impact of climate change on maize productivity across SSA is uncertain, but significant losses are expected, especially in Southern Africa (Conway et al., 2015; Lobell et al., 2008; Rosenzweig et al., 2014) and West Africa (Sultan & Gaetani, 2016). Smallholder farms in SSA usually obtain low maize yields, on average 1.8 t/ha in 2017 (FAOSTAT, 2018). These low yield levels are largely attributable to low fertilizer use, which averaged 12, 2 and 3 kg/ha for N, P and K respectively (FAOSTAT, 2018). With limited irrigation and inadequate access and use of nutrient inputs, water and nitrogen (N) stresses prevail (Folberth, Yang, Gaiser, Abbaspour, & Schulin, 2013).

Process-based soil-crop models can help quantify the potential impact of climate change on maize productivity in smallholder context whilst accounting for the water and N (and/or other plant nutrient) stresses (e.g. Kihara et al., 2012). Soil-crop models simulate biophysical processes resulting from plant genetics, crop management, soil properties and weather, thus tracking water, carbon, N, (phosphorous [P] to some extent) dynamics and energy balances as plants develop through the different phenological growth phases. As such, models must consider a range of complex processes and their interactions with weather, soil and crop management, for example, the effect of soil water dynamics on nutrient supply and uptake, or the influence of soil organic matter and organic amendments on nutrient availability during the growing season. The consideration of these soil- and climate-related processes increases model complexity, number of model parameters and data demand for model calibration. Compared to simulating irrigated systems with high nutrient inputs, where water and N are less often limiting factors,

the simulation of rainfed, low-input cropping systems requires more detailed model parameterization, especially of the soil processes. Model parameters related to soil water and nutrient processes are critical for the simulation of low input systems (Corbeels, Chirat, Messad, & Thierfelder, 2016; Jones et al., 2012). Main soil processes to be taken into account are: (a) soil water dynamics, including infiltration from rainfall, redistribution within the soil profile and evapotranspiration; (b) decomposition of soil organic matter and associated mineralization of N; and (c) N leaching below the root zone. Accurate simulation of the plant available water is crucial for simulation of crop water stress (Whitbread, Hoffmann, Davoren, Mowat, & Baldock, 2017), while mineralization and leaching largely determine soil N availability for plant uptake and therefore regulate N stress on crop growth. Hence, greater uncertainty related to model processes and parameterization is expected in the responses of low-input cropping systems to climate change. For example, it is known that N stress can strongly impact crop responses to variation in [CO₂], temperature and rainfall (Affholder, 1995; Ziska, Weerakoon, Namuco, & Pamplona, 1996). Furthermore, these cropping systems (which are often critical for local food security) are generally less well studied compared to the intensified midlatitude agricultural systems that have a greater global influence (Nendel, Melzer, & Thorburn, 2019).

The Agricultural Model Intercomparison and Improvement Project (AgMIP) was launched in 2010 to foster increased collaboration around crop model improvement across modelling groups (Rosenzweig et al., 2013). Crop model intercomparisons have proven useful to compare consistency among models and quantify uncertainty in model predictions (Asseng et al., 2013; Bassu et al., 2014; Fleisher et al., 2017; Li et al., 2015; Ruane et al., 2017). They have reinforced the benefit of multimodel approaches, as they help identify sources of uncertainty (associated with model parameters, model structure and model users; Tao et al., 2018, 2020). The ensemble mean or median usually resulted as best predictors for multiple crops and for different soil and plant variables (Martre et al., 2015; Wallach et al., 2018). For example, the intercomparison of maize models (Bassu et al., 2014) allowed assessing model uncertainty in the simulated impact of climate change on maize yields under high-production conditions, that is, high-input, near-potential crop growth conditions where N fertilizer inputs ranged from 60 to 255 kg N/ha and sites were irrigated or had good rainfall and thus grain yield ranged from 5 to 11 t/ha. These conditions differ considerably from the context of smallholder farmers across SSA. Bassu et al. (2014) analysed the effect of model structure related to above-ground crop growth processes (e.g. simulation of net primary production of the canopy as

influenced by temperature and $[CO_2]$ but did not deal with soil-related processes (e.g. N mineralization and N leaching).

Several studies relying on the calibration of a single crop model with field data, have investigated model accuracy under current climate and explored the impact of climate change on low-input smallholder systems in SSA (e.g. Amouzou et al., 2019; Freduah et al., 2019; Rurinda et al., 2015; Traore et al., 2017). However, the use of a single crop model precludes an analysis of simulation uncertainty related to model structure. A few studies investigated climate change and N input interactions in smallholder context with two different crop models (Faye, Webber, Naab, et al., 2018; Guan, Sultan, Biasutti, Baron, & Lobell, 2017). Although these studies did address the issue of model uncertainty, they did not embrace the wide diversity of existing crop models. The AgMIP Global Gridded Crop Model Intercomparison study has conducted a series of model sensitivity tests to $[CO_2]$, temperature, water and N conditions (Franke et al., 2020), but the applied models operated on a macrolevel ($\sim 0.5^\circ$ spatial resolution) and were not calibrated against field data to capture the conditions of controlled field experiments in SSA. Thus, the accuracy and uncertainty of model simulations and model responses to the interactions between N supply and climate change in low-input systems have not been assessed for multimodel ensembles. Understanding climate change and N fertilizer input interactions will help prioritize relevant recommendations for adaptations to climate change for African smallholder farmers who currently use low levels of N inputs but will likely intensify their cropping systems with additional mineral fertilizers (Vanlauwe et al., 2014).

This study addresses three main questions, namely: (a) What is the accuracy and uncertainty of current crop model simulations of maize yield and other intermediary variables for field experiments in the context of rainfed smallholder systems in SSA? (b) How does N fertilizer input interact with maize response to climate change (increase in $[CO_2]$, increase in temperature and changes in rainfall)? (c) Do model structure (i.e. formalisms to account for N dynamics) and model consistency

(i.e. the ability to accurately simulate multiple variables) explain the simulated interaction between climate change and N fertilizer input?

By doing so, we explore the hypotheses that (a) model simulations of existing maize experiments in smallholder context in SSA are more uncertain with lower accuracy than simulations of intensified cropping systems in temperate regions; (b) crop models simulate a lower impact of $[CO_2]$, temperature and rainfall changes in low-input (e.g. 0 kg N/ha) than in high-input conditions (e.g. 160 kg N/ha); and (c) model structure and consistency of simulations for multiple soil and plant variables can explain diverging responses to the interaction between N inputs and climate change.

2 | MATERIALS AND METHODS

2.1 | Experimental data

We searched the literature for peer-reviewed publications in which maize field experiments under rainfed conditions were conducted during at least two cropping seasons in representative maize growing areas in SSA. The studies needed to include measurements of crop phenology (flowering and maturity dates), final grain yield and above-ground biomass at maturity, and in-season soil water dynamics for at least one growing season. Studies chosen represent a diversity of climates, soils and management conditions found across SSA for maize production. This resulted in the selection of five experimental studies that were conducted at sites respectively in Benin, Mali, Ghana, Rwanda and Ethiopia (Figure 1; Table 1). Besides the required data on crop phenology, grain yield, above-ground plant biomass and in-season soil water dynamics, data on in-season leaf area index (LAI) was available in at least one of the two seasons at each site except Benin. Ghana and Benin also included additional measurements of above-ground plant N accumulation during crop growth (Benin) and at maturity (Benin and Ghana). Cultivars differed across sites and

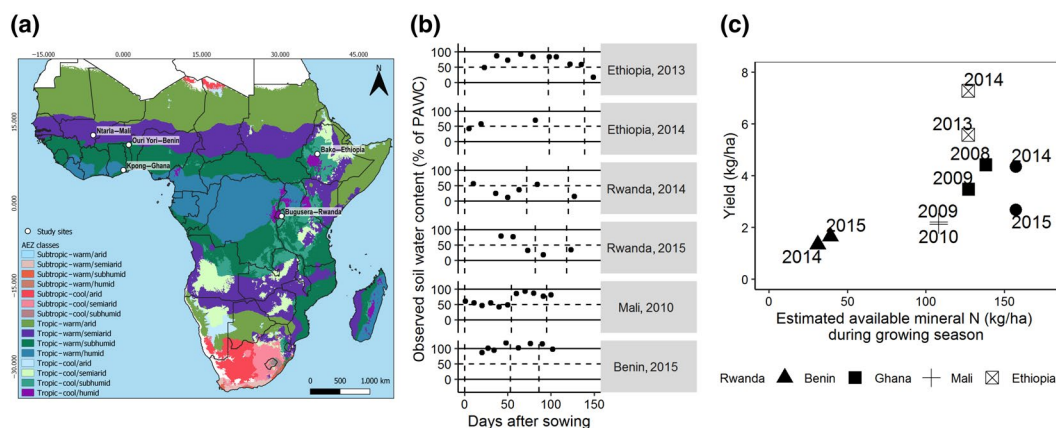


FIGURE 1 (a) Map of sub-Saharan Africa showing the five study sites representative of FAO tropical agroecological zones where maize cultivation is possible. (b) Observed soil water content to maximum rooting depth in the six experiments where soil water was monitored (vertical lines from left to right are sowing, anthesis and maturity dates). (c) Observed maize grain yield at the five sites for two growing seasons (10 experiments) as a function of estimated available mineral nitrogen (N), that is, the summation of initial soil mineral N, applied mineral and organic N and mineralized soil organic N and manure N over the whole growing season (for Ethiopia and Rwanda, initial mineral N measurements were not available). PAWC, plant available soil water capacity

TABLE 1 Characteristics of the five sites and 10 experiments selected for model evaluation of maize yield simulation in rainfed smallholder farming systems across sub-Saharan Africa

	Site				
General information					
Country	Benin	Mali	Ghana	Rwanda	Ethiopia
Location	Ouri Yori	Ntarla	Kpong	Bugesera	Bako
Source	Amouzou et al. (2018)	Traore et al. (2014)	MacCarthy et al. (2015)	Ndoli et al. (2018)	Sida et al. (2018)
Latitude	10.82	12.58	6.16	−2.35	9.13
Longitude	1.07	−5.70	0.06	30.27	37.10
Elevation (m)	213	302	22	1,400	1,700–2,000
FAO agro-ecological zoning	Tropic-warm semi-arid	Tropic-warm semi-arid	Tropic-warm subhumid	Tropic-cool subhumid	Tropic-cool subhumid
Rainfall pattern	Unimodal	Unimodal	Bimodal	Bimodal	Unimodal
Average growing season	June– September	June– September	March–July and August– December ^a	September– January and February–July ^b	June– October
Soils					
Soil type (FAO)	Gleyic Alisol	Ferric Lixisol	Vertisol	Humic Ferralsol	Nitisol
Soil texture	Loamy sand	Loamy sand	Clay	Sandy loam	Clay
Maximum rooting depth (cm)	60	120	100	100	120
Plant available soil water capacity (mm to maximum rooting depth)	105	167	93	104	202
SOC (%; 0–30 cm)	0.28	0.2	0.57	1.65	0.65
Total nitrogen (%; 0–30 cm)	0.023	0.015	0.048	0.138	0.059
Management					
Cultivar	EVDT-97 STR (OPV ^c)	Suwan 1-SR (OPV ^c)	Obatampa (OPV ^c)	ZM607 (OPV ^c)	BH540 (Hybrid)
Sowing dates (DOY ^d)	176, 185	151, 163	111, 105	282, 267	161, 158
Manure input (t/ha)	0	3	0	0	0
N content in manure (%)	—	1.6	—	—	—
Total applied N fertilizer (kg N/ha)	0	85	80	64	87
Total applied P fertilizer (kg P/ha)	0	26	30	20	9
Total applied K fertilizer (kg K/ha)	0	16	37	0	0
Phenology					
Anthesis (DAP ^e)	52, 53	56, 54	65, 60	72, 82	97, 98
Maturity (DAP ^e)	80, 86	97, 95	105, 106	120, 118	138, 139
Experimental year climate					
Experimental year (first experiment)	2014	2009	2008	2013–2014	2013
Mean growing season temperature	27.9	26.6	27.7	22.8	21.1
Mean growing season precipitation	516	549	536	217	476
Experimental year (second experiment)	2015	2010	2009	2014–2015	2014
Mean growing season temperature (season 2)	27.1	26.9	27.6	23.1	20.5
Mean growing season precipitation (season 2)	810	705	455	351	923
Baseline climate (1980–2010)					
Mean growing season temperature	25.5	28.3	27.6	21.9	20.6
Mean growing season precipitation	641	582	442	331	939

^aOnly March–July was considered for the experiments.^bOnly September–January was considered for the experiments.^cOpen pollinated variety.^dDOY, Day of the year; First and second value indicate season 1 and season 2 experiments respectively.^eDAP, Days after planting; First and second value indicate season 1 and season 2 experiments respectively.

TABLE 2 Model grouping into four groups according to characteristics linked to the simulation of N and additional characteristics of the models. Class 3a and 3b were determined after the analysis of model ranking (based on relative root mean square error) when simulating all variables of interest (see Section 2.4 for detailed description of the classification). In bold, models that participated in a previous maize intercomparison in high input systems (Bassu et al., 2014). Underlined models are the 10 highest ranked models (among class 3 models) for grain and biomass simulation (see Section 2.4 for detailed description of the classification)

Model class	Effect of N input	Daily N module	Model	Model reference ^a	Leaf area development and light interception ^b	Light utilization ^c	Yield formation ^d
1	No	No	GLAM	Challinor, Wheeler, Craufurd, Slingo, and Grimes (2004)	S	RUE, TE	B, HI
			MCWLA	Tao and Zhang (2010)	S	P-R	B, HI
2	Yes	No	PEGASUS	Deryng, Conway, Ramankutty, Price, and Warren (2014)	S	RUE	B, Prt
			SARRA-H	Baron et al. (2005)	S	RUE	HI, Prt
			CELSIUS	Ricome et al. (2017)	S	RUE	B, Gn, HI_mw
3a	Yes	Yes	<u>APSIM 7.9</u>	Holzworth et al. (2014)	S	RUE	Prt
			<u>DNDC</u>	Smith et al. (2020)	S	TE	HI
			<u>HERMES</u>	Kersebaum (2011)	D	P-R	Prt
			<u>DSSAT-IXIM-Maize + Century</u>	Lizaso et al. (2011)	D	P-R	Gn
			<u>DSSAT-IXIM-Maize + Ceres-SOM</u>	Lizaso et al. (2011)	D	P-R	Gn
			<u>MONICA</u>	Nendel et al. (2011)	D	P-R	Prt
			<u>SALUS</u>	Basso, Cammarano, Troccoli, Chen, and Ritchie (2010)	S	RUE	HI, Prt
			<u>SIMPLACE-Lintul + ET Hargreaves + heat stress with air temperature</u>	Gaiser et al. (2013)	S	RUE	Prt
			<u>STICS</u>	Brisson et al. (2002)	S	RUE	B, Gn, HI, mw
3b	Yes	Yes	<u>DSSAT-CERES-Maize + Century</u>	Ritchie, Singh, Godwin, and Bowen (1998)	S	RUE	Gn
			AGRO-IBIS	Twine et al. (2013)	S	P-R	B, Prt
			<u>APSIM 7.10</u>	Holzworth et al. (2014)	S	RUE	Prt
			<u>DSSAT-CERES-Maize + Ceres-SOM</u>	Ritchie et al. (1998)	S	RUE	Gn
			<u>EXPERT-N-Ceres</u>	Biernath et al. (2011)	S	RUE	B, Gn
			<u>EXPERT-N-Spass</u>	Biernath et al. (2011)	D	P-R	Prt
			<u>EXPERT-N-Sucros</u>	Biernath et al. (2011)	D	P-R	Prt
			<u>MAZSIM</u>	Kim et al. (2012)	D	P-R	HI, Prt
			<u>RZWQM2</u>	Sadhukhan et al. (2019)	S	RUE	B, Gn, Prt
			<u>SIMPLACE-Lintul + ET FAO-56 + heat stress with crop temperature</u>	Faye, Webber, Diop, et al. (2018)	S	RUE	Prt
			<u>SWB</u>	van der Laan, Stirzaker, Annandale, Bristow, and du Preez (2010)	S	RUE, TE	Prt

^aMore references and model documentation can be found in Table S2.

^bS, simple-unilayer (e.g. leaf area index); D, detailed multilayer (e.g. canopy layers).

^cRUE, radiation use efficiency approach; P-R gross, photosynthesis–respiration; TE, compute water use first, then biomass growth from transpiration efficiency.

^dB, total (above-ground) biomass; Gn, number of grains; HI, fixed harvest index; HI_mw, Harvest Index modified by water stress; Prt, partitioning during reproductive stage.

^eFunction of: T, temperature; DL, photoperiod (day length); O, other water/nutrient stress effects considered.

^fCD, convective dispersive; EXP, exponential; LIN, linear; SIG, sigmoidal.

^gE = Eta/Etp; O, leaf energy balance, leaf and soil water potential effects on photosynthesis and leaf expansion; S, soil available water in root zone.

^hR, reproductive organ (sink); V, vegetative (source).

ⁱC, 'Tipping bucket' capacity approach; R, Richards approach.

^jO, leaf energy balance (MZ), Hargreaves Dual crop coefficient method (SI2), water demand in plant, root water uptake, closes surface energy budget (AG); P, Penman; PM, Penman–Monteith; PT, Priestley–Taylor; SW, Shuttleworth–Wallace.

^kB, microbial biomass pool; C, C model; N, N model; P(x), x is the number of organic matter pools.

^lF, Farquhar model; GY, Grain Yield; LF, leaf-level photosynthesis–rubisco or on quantum efficiency and light-and-CO₂-saturated leaf photosynthesis (Amax); PT, photosynthesis and transpiration; RUE, radiation use efficiency; T, Stomatal conductance; TE, transpiration efficiency.

Crop phenology ^e	Root distribution over depth ^f	Simulation of N leaching	Simulation of heat stress	Type of water stress ^g	Type of heat stress ^h	Water dynamics ⁱ	Evapotranspiration ^j	Soil CN model ^k	Process modified by elevated CO ₂ ^l
T, DL	LIN	No	Yes	E	R	C	PT	—	RUE, TE
T	EXP	No	Yes	E	V, R	R	PM	—	—
T	LIN	No	Yes	E, S	V, R	C	PT	C, P(1)	RUE, TE
T	LIN	No	No	S	—	C	PM	—	RUE, T
T, DL	LIN	No	Yes	S	V, R	C	PM	N	RUE
T, DL	EXP	Yes	Yes	S	V	C	PT	CN, P(3), B	RUE, TE
T	EXP	Yes	Yes	S	R	C	PM	CN, P(5), B	PT
T, DL, O	EXP	Yes	No	E, S	—	C	PM	N, P(2)	LF, T
T, DL	EXP	Yes	Yes	E	R	C	PT	CN, P(2), B	RUE, T
T, DL	EXP	Yes	Yes	E	R	C	PT	CN, P(1)	RUE, T
T, DL, O	EXP	Yes	Yes	E	V	C	PM	CN, P(6), B	—
T, DL	EXP	Yes	Yes	E	V	C	PT	CN, P(3), B	—
T, DL	EXP	Yes	No	E, S	—	C	O	CN, P(7), B	RUE, TE
T, DL, O	SIG	Yes	Yes	E	V, R	C	SW	CN, P(2), B	RUE, T
T, DL	EXP	Yes	Yes	E	R	C	PT	CN, P(2), B	RUE, T
T	EXP	Yes	Yes	S	V, R	R	O	C, N, P(2)	F
T, DL	EXP	Yes	Yes	S	V	C	PT	CN, P(3), B	RUE, TE
T, DL	EXP	Yes	Yes	E	R	C	PT	CN, P(1)	RUE, T
T, DL	EXP	Yes	Yes	E, S	V	R	PM	CN, P(3), B	-
T, DL	EXP	Yes	Yes	E, S	V	R	PM	CN, P(3), B	-
T	EXP	Yes	Yes	E, S	V	R	PM	CN, P(3), B	-
T, DL	CD	Yes	Yes	O	V, R	R	P, O	N, P(1), B	LF, T, F
T, DL, O	EXP	Yes	Yes	E, S	V, R	R	SW	C, N, P(1), B	PT
T, DL	EXP	Yes	Yes	E, S	R	C	PM	CN, P(7), B	RUE, TE
T	LIN	Yes	No	S	—	C	PM	CN, P(4)	RUE, TE

were open-pollinated varieties, except in Ethiopia where a hybrid was grown. Total applied N fertilizer was 0, 64, 80, 85 and 87 kg/ha in the sites in Benin, Rwanda, Ghana, Mali and Ethiopia respectively. There was no irrigation at any of the sites (Table 1). The experiments were extensively described, for Benin by Amouzou, Naab, Lamers, and Becker (2018), for Mali by Traore et al. (2014), for Ghana by MacCarthy, Akponikpe, Narh, and Tegbe (2015), for Rwanda by Ndoli et al. (2018) and for Ethiopia by Sida, Baudron, Hadgu, Derero, and Giller (2018). Soil water content to maximum rooting depth was expressed as a percentage of plant available soil water capacity (PAWC), which was calculated as the difference between the water content at the drained upper limit and the water content at the lower extraction limit of the maize crop (both over the maximum rooting depth; Table 1; Table S1). The soil initial conditions (moisture and mineral N) for the simulations are given in Table S1.

To characterize each experiment regarding soil fertility, total available mineral N during the crop growing season was estimated by summing (a) measured soil mineral N prior to sowing (0–30 cm topsoil layer); (b) N inputs from mineral fertilizer applied; and (c) N mineralized from soil organic N in the topsoil (0–30 cm) and from manure applied. Manure was applied in Mali only (Table 1). Nitrogen mineralized from soil organic matter and applied manure was estimated considering a mineralization rate of 1.5% of soil organic N per growing season, corresponding to commonly reported average mineralization rates in SSA (Bationo, Kihara, Vanlauwe, Waswa, & Kimetu, 2007; Masvaya, Nyamangara, Descheemaeker, & Giller, 2017). While PAWC and the 1.5% mineralization rate were used to describe the experimental settings, this information was not forwarded to the modelling groups and they were left to address PAWC and soil N availability as per their model usual procedure.

Weather data (daily solar radiation, minimum and maximum temperatures and rainfall) for the years of the experiments were obtained from records at onsite meteorological stations at all sites. Wind speed and relative humidity for the years of the experiments were obtained from the AgMERRA climate data set (Ruane, Goldberg, & Chrysanthacopoulos, 2015). For the model simulation of the baseline climate (1980–2010), daily solar radiation, minimum and maximum temperatures and rainfall were obtained from records at the onsite meteorological stations in Benin, Mali and Ghana and obtained from AgMERRA in Ethiopia and Rwanda. Wind speed and relative humidity were obtained from AgMERRA for the baseline climate at all sites.

2.2 | Model characteristics and calibration procedure

An ensemble of 25 crop models was used for this study (Table 2; Table S2).

These crop models present structural differences in how they model crop growth and soil processes (e.g. leaf area and light interception, grain yield formation, soil water dynamics, nitrate leaching,

see Table 2). Of particular interest for this study was how models simulate the effect of N supply on crop growth and yield. This aspect is described in Section 2.4.2.

Model simulations were executed by individual modelling groups within AgMIP (Rosenzweig et al., 2013). The model calibration entailed two phases, that is (a) partial and (b) full calibration. For partial calibration, minimum input values required to run the model were provided, that is, soil characteristics, initial soil conditions (moisture at all sites and mineral N for Benin, Mali and Ghana), crop management (sowing date, mineral and organic fertilizer inputs), weather and observed flowering and physiological crop maturity dates (Table 1; Table S1). In the partial calibration phase, adjustment by modelling groups to observed values was limited to setting the model parameters involved in the simulation of the time to anthesis and time to maturity. For full calibration, all measured crop and soil variables of the experiments (see Section 2.1) were provided. Modelling groups could adjust the model parameters they deemed relevant to improve the model fit to observed data, using their usual methods (e.g. manual tuning or use of an optimization program). There was no knowledge sharing between the modellers and the researchers who conducted the trials during the calibration steps to guarantee that modellers from the different groups had an equal level of information on the field experiments. All sites and growing seasons were used for model calibration and no independent evaluation of simulations was performed. Each modelling group used one unique crop model. The different versions of APSIM, DSSAT and SIMPLACE-LINTUL (see Table 2) were each used by single modelling groups.

2.3 | Model response to [CO₂], temperature, rainfall and N fertilizer

Responses of fully calibrated models to variation in [CO₂], temperature and rainfall were assessed, in interaction with varying mineral N input levels. Baseline years (1980–2010) were simulated with the crop management of the second growing season at each site (Table 1) for three levels of N fertilizer (0, 80, 160 kg N/ha). Response to [CO₂] was analysed for imposed concentrations of 360 and 720 ppm. Response to temperature was assessed by increasing daily minimum and maximum temperatures by 4°C. Response to rainfall was analysed by multiplying baseline daily rainfall by 0.5 and 1.50. These levels represent drastic but plausible changes in environmental conditions that allow testing the sensitivity of crop models (Rosenzweig et al., 2013). A doubling of [CO₂] (to 720 ppm) and a +4°C temperature increase correspond to possible conditions around 2080 as predicted by climate models under RCP 8.5 (IPCC, 2013). Factorial combinations of changes in [CO₂], temperature and rainfall were not considered. For each level of [CO₂], temperature and rainfall, model simulations were run for three levels of N fertilizer (0, 80, 160 kg N/ha split in two applications during the crop growing season).

2.4 | Data analysis

2.4.1 | Model accuracy, uncertainty and response to climate change factors

We analysed model accuracy for simulated grain yield, above-ground plant biomass, maximum LAI, above-ground plant N at maturity, harvest index and in-season soil water content. Observed and simulated values were compared using the root mean square error (RMSE) and relative RMSE (rRMSE) for each of the above variables:

$$\text{RMSE}_m = \sqrt{\frac{1}{n} \sum_{i=1}^n (O_i - P_{i,m})^2}, \quad (1)$$

$$\text{rRMSE}_m = \frac{\text{RMSE}_m}{\bar{O}} \times 100, \quad (2)$$

where O_i and $P_{i,m}$ are the observed and simulated values (for model m) for the i th measurement, n is the number of observations (i.e. the sum over sites, seasons and over measurement dates per site for in-season soil water content) and $\bar{O}$ is the mean of the observed values.

To analyse uncertainty in model simulations, the coefficient of variation (CV) of the simulations with the 25 models for a given variable at a given site (both seasons) was computed as:

$$\text{CV}_s = \frac{\sigma_s}{\bar{p}_s} \times 100, \quad (3)$$

where σ is the standard deviation of the simulated values at site s and $\bar{p}$ is the mean of simulated values at site s . CV_s was also averaged across all sites.

We assessed the value of using an ensemble of models to simulate grain yield. We started by computing the average simulated yields with ensembles of increasing number of models ($n = 1$ –25) for each of the 10 experiments. Then we computed the relative variation between these average simulated yields and the measured yield in the experiments:

$$U_n = \frac{\sum_{i=1}^{10} |P_{ni} - O_i|}{\sum_{i=1}^{10} O_i} \times 100, \quad (4)$$

where O_i and P_{ni} are the observed and average simulated values (for a model ensemble of size n) for the i th experiment. Starting from two to 25 models, U_n was computed for a random sampling of 5% of all the $\frac{25!}{n!(25-n)!}$ combinations of models. For $n = 1$, all combinations were evaluated.

The relative model response to a given climate change factor was computed for a particular model as:

$$R_m = \frac{P_{\text{future},m} - P_{\text{baseline},m}}{P_{\text{baseline},m}}, \quad (5)$$

where $P_{\text{future},m}$ is the 31 year (1980–2010) simulated average of model m for the variable of interest (e.g. grain yield) under changed climate (altered $[\text{CO}_2]$, temperature or rainfall, see above) and $P_{\text{baseline},m}$ is the 31 year simulated average of model m for the same variable under the baseline climate (1980–2010). Here we analysed the relative model response to climate change for doubling $[\text{CO}_2]$ (360–720 ppm), temperature +4°C, 50% of baseline rainfall and 150% of baseline rainfall for N fertilizer applications of 0, 80 and 160 kg N/ha.

The relative model response to climate change R_m can take either positive or negative values. Since the CV between models is of limited value to assess prediction uncertainty in this case, we calculated the interquartile range (IQR) of the ensemble relative to change in the simulated variable of interest (e.g. grain yield).

2.4.2 | Model classification

We first investigated whether model structural characteristics had an influence on the model response to climate change with different N inputs. To do so, we classified the models according to (a) their capability to simulate crop responses to N inputs; and (b) the existence of an N module with a daily time-step in the model (Table 2).

Two models (MCWLA and GLAM) did not handle crop response to N and formed the first class. Three models (PEGASUS, SARRA-H and CELSIUS) simulated responses to N input but did not include a detailed N module. These models formed the second class. In these three models, a fixed N stress factor is applied to daily biomass production. In PEGASUS, values of seasonal N stress factor were obtained by the correlation of national N fertilizer inputs and gridded yield gap fraction data (Deryng, Sacks, Barford, & Ramankutty, 2011). In CELSIUS and SARRA-H, a seasonal N stress factor is calculated as the ratio of total seasonal available N to the crop N uptake required for non-limited growth. In CELSIUS, total seasonal available N is calculated with mineralization coefficients obtained from the literature (Ricome et al., 2017). In SARRA-H, the N stress factor was calibrated with on-farm and on-station experiments across West Africa.

Twenty models handled crop responses to N and had a detailed N module with daily time-step calculations of soil and plant N processes; they formed the third class of models (Table 2). All class 3 models use as inputs (a) soil mineral N content at initiation of the simulation; and (b) the amounts of fertilizer N applied at specified dates during the cropping season. These models include the explicit representation of a number of organic C pools in the soil (Table 2) and functional processes of organic matter mineralization to compute the availability of mineral N for crop uptake. In these models, daily mineralization of organic nitrogen is simulated with one to seven organic carbon and nitrogen pools (Table 2) with specific decomposition rates. Simple approaches usually identify a labile (fast decomposition rate) and a stable (slow decomposition rate) organic matter pool. More complex models have additional microbial biomass-related pools to simulate

the role of soil organisms in the N mineralization–immobilization turnover process during decomposition.

Within this third class of models, we investigated whether model consistency, that is, model ability to adequately simulate different soil and plant variables, could explain model performances and model responses to climate change and its interaction with N fertilizer inputs. The indicator used for model consistency was the sum of ranks (Martre et al., 2015) for rRMSE over the variables of interest (i.e. grain yield, total above-ground biomass, maximum LAI, total above-ground plant N, harvest index and soil water contents). Models below the median sum of ranks for rRMSE over all the variables were classified as 'most consistent' models (class 3a), and models above the median as 'less consistent' models (class 3b; Table 2). An alternative ranking of models was computed based on the sum of ranks for grain yield and total above-ground biomass only (the two variables available for all experimental situations). Models below the median sum of ranks for rRMSE over these two variables were classified as 'highest ranked' models (for grain and biomass; Table 2).

The effect of model class on the model response to climate change (doubling $[\text{CO}_2]$, temperature $+4^\circ\text{C}$, 50% of baseline rainfall and 150% of baseline rainfall) was examined using linear mixed model regression analysis with model class (3a or 3b) and N input as fixed factors and site as a random factor. *p*-values to test the significance of model class were obtained by likelihood ratio tests of the full regression model (including all fixed and random factors) against a regression model with only N input and site effects. Visual inspections of residuals plots did not reveal deviations from normality or heteroscedasticity. The analysis was done using R (R Core Team, 2019; <http://www.R-project.org>) and the linear mixed-effect model was coded and tested with the R package *lme4* (<http://cran.r-project.org/web/packages/lme4/index.html>). We performed the likelihood ratio test with the ANOVA function.

3 | RESULTS

3.1 | Characterization of sites and crop experiments

Seasonal rainfall (from maize sowing to harvest) varied greatly across sites and seasons, from 217 mm (Rwanda, 2014 season) to 923 mm (Ethiopia, 2014 season; Table 1). Seasonal rainfall was low in Rwanda in 2014 but residual soil water at sowing was substantial (i.e. 57% of PAWC). Crop water stress occurred during the two experimental years in Rwanda (Figure 1b). In Benin, Mali and Ethiopia, observed soil water contents never went below 50% of PAWC during crop growth in the experiments where soil water was monitored (Figure 1b), indicating a likely low occurrence of crop water stress. In Ghana, water content was monitored to 30 cm soil depth only, so these data were of limited value for analysing water stress. Overall, observed maize grain yields were not correlated to seasonal rainfall (Figure S1), confirming the role of N (Figure 1c) and other crop growth limiting factors in determining grain yield.

Estimated total available mineral N during the crop growing season varied widely across sites (Figure 1c). It was lowest at the experimental site in Benin, where there was no fertilizer input (Table 1). Total available mineral N was highest in the experiments in Rwanda, due to fertilizer inputs and a high soil organic N content compared with experiments in the other sites (Table 1). Although maize yield tended to increase with estimated total mineral N availability (see Section 2.1), the correlation was not significant (Figure 1c).

3.2 | Model simulations of the experiments

3.2.1 | Model accuracy

When partially calibrated to phenology only, most models failed to accurately reproduce grain yield variations across sites and experiments (Figure 2a); rRMSE averaged across models for grain yield was 63% (Figure 2b). Full calibration greatly improved the models' ability to reproduce observed grain yields (Figure 2a); rRMSE averaged across models decreased to 26% (Figure 2b). The median of the fully calibrated model ensemble closely approximated observed grain yields (Figure 2a). Improvement in model accuracy with full calibration was also important for above-ground biomass at maturity and maximum LAI but was more limited for above-ground plant N at maturity and harvest index (Figure 2b). Maize phenology was accurately simulated by the fully calibrated models, with rRMSEs of 8% and 13% for the sowing-anthesis and anthesis-maturity durations respectively. Regarding the temporal dynamics, the range of simulated values of in-season LAI, soil water content, above-ground plant biomass and above-ground plant N mostly enveloped the observed values (Figure S3). With exception of the 2013 season in Ethiopia, most models were able to reproduce seasonal soil water dynamics, a crucial variable for simulating crop growth when water stress occurs. The increase in soil water up to field capacity during (a) the vegetative crop phase in the field experiment in Benin in 2015; and (b) during the reproductive phase in the field experiment in Mali in 2010 was well reproduced by most models. The decrease in soil water below 50% of PAWC early in the season in 2014 and later in the season in 2015 in Rwanda was also well simulated by most models. Main disagreements between model simulations and field measurements occurred (a) in Rwanda in 2015, for which most models underestimated LAI and overestimated above-ground plant biomass; and (b) in Ethiopia in 2013, for which all models underestimated observed above-ground plant biomass and soil water. The latter may, however, be due to errors in rainfall recording or poor calibration of the moisture probes used to estimate soil water.

Nitrogen mineralized from soil organic matter and N leached below the root zone were not measured in the field experiments so we could not assess model prediction accuracy for these variables. The ensemble median of simulated N mineralization, averaged over the two crop growing seasons, was 22, 20, 39, 43 and 38 kg/ha in Benin, Mali, Ghana, Rwanda and Ethiopia respectively. These simulated values matched reasonably well with the empirical estimates of

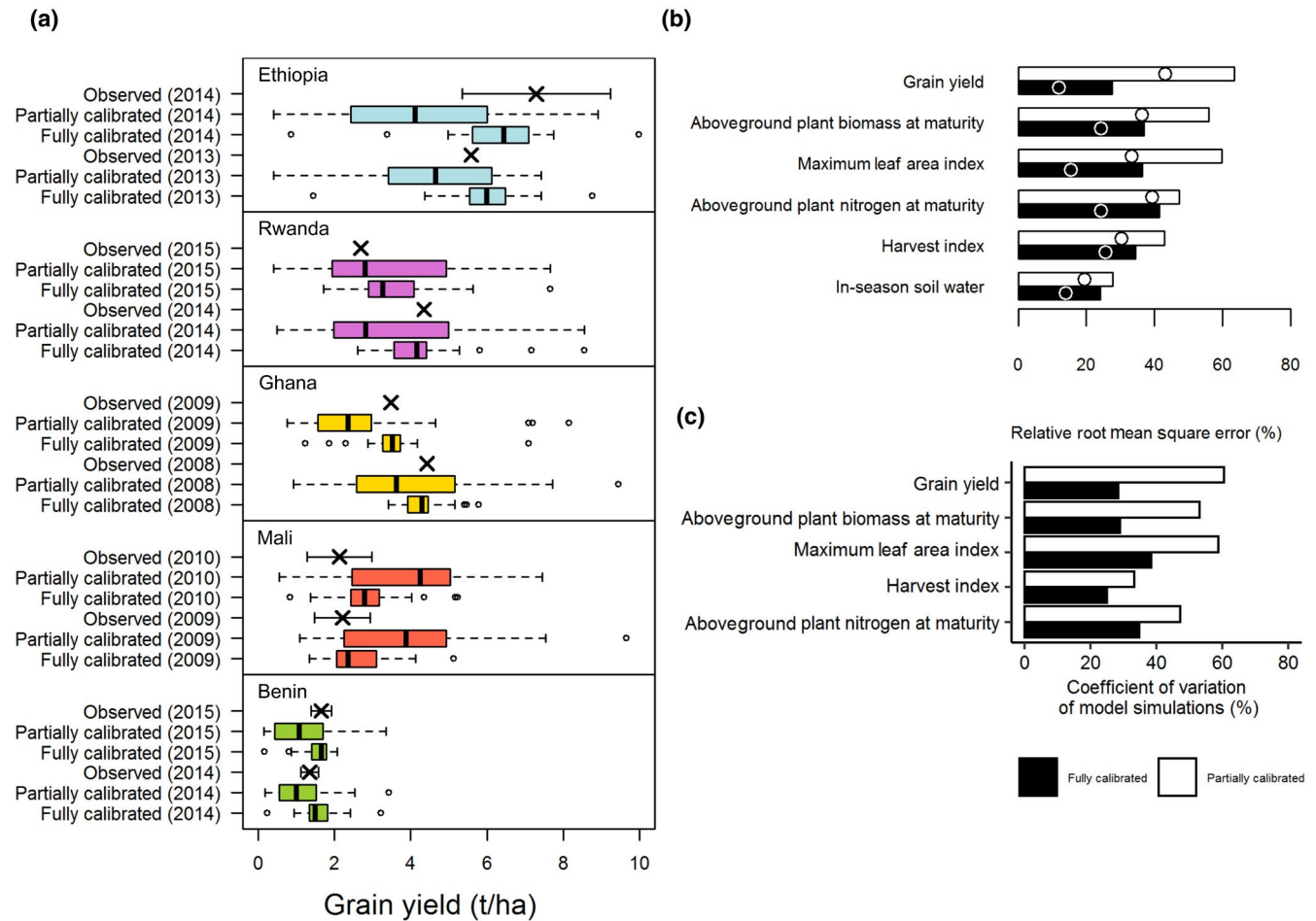


FIGURE 2 (a) Observed (crosses with standard deviation if known) and simulated (box plots) grain yields. Simulations are from an ensemble of 25 partially and fully calibrated models. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range. Black open dots are outliers. (b) Relative root mean square error (rRMSE; averaged across all models) of simulated–observed comparison for six variables of interest. For above-ground plant nitrogen the comparison was possible for four of the 10 experiments only (Benin and Ghana). Open dots indicate rRMSE of ensemble median. (c) Coefficient of variation (averaged across sites) of 25 model simulations for five variables

N mineralization using a rate of 1.5% of soil organic N (see Section 3.1), that is, 16, 10, 32, 93 and 40 kg/ha in Benin, Mali, Ghana, Rwanda and Ethiopia respectively. The ensemble median of simulated N leaching, averaged over the two crop growing seasons, was 11, 15, 2, 2 and 4 kg/ha in Benin, Mali, Ghana, Rwanda and Ethiopia respectively.

3.2.2 | Model prediction uncertainty

Full model calibration resulted in a reduction of prediction uncertainty (expressed as CV), and this reduction was larger for grain yield and above-ground plant biomass at maturity than for the other plant-related variables (maximum LAI, above-ground plant N at maturity and harvest index; Figure 2c). Overall, there was no clear indication that model prediction uncertainty was largest in the most constrained (N-limiting) sites (e.g. Benin; see Figure S2). Prediction uncertainty was relatively low for maize phenology (full calibration),

with a CV of 9% for the sowing-anthesis duration, and 16% for the anthesis-maturity duration. Prediction uncertainty of simulated N mineralization was large, both with partial (CV of 90%) and full calibration (CV of 85%). A similar behaviour was found for simulated N leaching, with CVs of 171 and 136% with partial and full calibration respectively.

The average absolute difference between measured and simulated grain yield decreased rapidly with the number of models considered in an ensemble (Figure 3). A least eight calibrated models were needed to fall below a 13.5% threshold, that is, the CV of measured yield typically obtained in experimental plots (Taylor, Payton, & Raun, 1999).

3.2.3 | Model classification

Models of class 1 and 2 simulated grain yield accurately with rRMSE values equal to or below 18% (Table 3). Some models of these classes

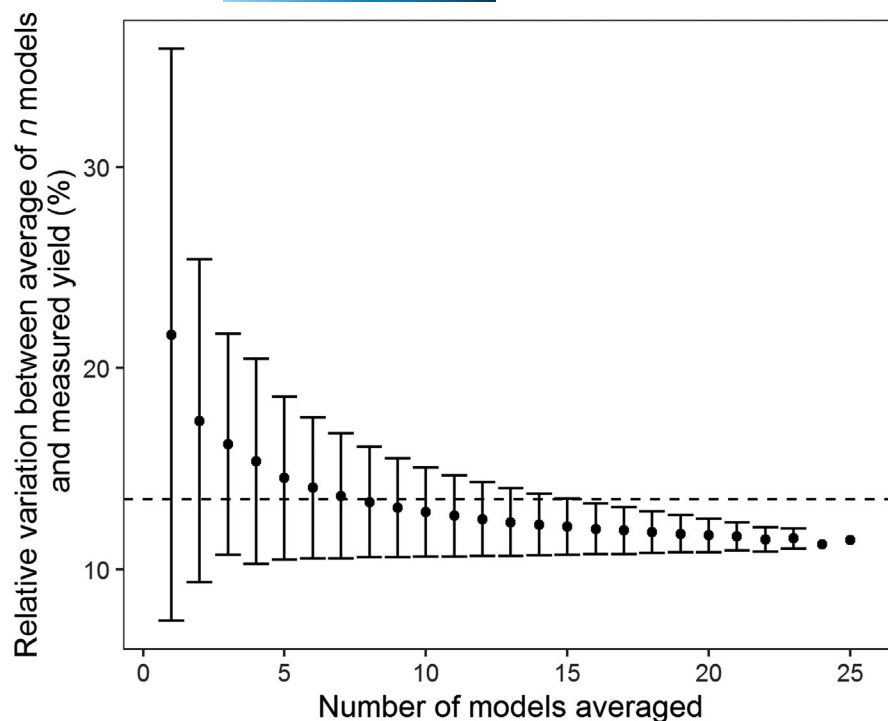


FIGURE 3 Relative variation (mean $\pm$ SD) between average of n models and measured grain yield in the 10 experiments at five sites across sub-Saharan Africa. Models were randomly selected among the 25 calibrated models that simulated yield for the 10 experiments. The horizontal dotted line is the 13.5% threshold, that is, the coefficient of variation for measured yields typically obtained in experimental plots (Taylor et al., 1999)

also performed well for the other variables (i.e. total above-ground biomass at maturity, maximum LAI, harvest index and soil water) with rRMSE values close to or below 30%.

The 10 'most consistent' models of class 3, that is, models below the median sum of rank for rRMSE across all variables (Figure S4) were grouped in class 3a, and the others were placed in class 3b (Table 2). The most consistent crop model (DNDC) when considering all variables had a sum of rank of 32 (Table 3). Decrease in model uncertainty from partial to full calibration for simulated grain yield was similar for both model classes 3a and 3b, that is, 57% and 42% for class 3a and 3b respectively. However, the decrease in model uncertainty for above-ground plant N at maturity was greater for models of class 3a than 3b, that is, 44% and 11%, respectively, indicating a likely greater effect of calibration on N supply and N uptake for models of class 3a than 3b. After full calibration, class 3a models had a significantly ($p < .05$) smaller RMSE for grain yield, above-ground plant biomass at maturity, above-ground plant N at maturity, maximum LAI, harvest index and in-season soil water content compared with class 3b models. Most of the modelling groups (60%) who used class 3a models reported calibration of soil parameters related to the size of the different soil organic matter pools to adjust the amount of N mineralized from soil organic matter and to improve the match with observed above-ground plant N, while only 10% of the class 3b modelling groups reported such parameterization procedure (Table S3). Similarly, the majority (60%) of the class 3a modelling groups reported calibration of parameters related to soil water dynamics (e.g. moisture contents at field capacity and wilting point, soil water evaporation coefficients) to mimic observed soil water dynamics, while only 30% of the class 3b modelling groups reported such parameterization procedure (Table S3). Classifying class 3 crop models according to grain yield

and above-ground biomass only (i.e. the variables that were observed for all sites and experiments) led to minor changes in the classification; the eight 'most consistent' models were also among the eight best models when ranked based on grain yield and above-ground biomass only (see underlined models in Table 2).

3.3 | Model ensemble response to climate change and N inputs

Across sites and levels of N fertilization, the model ensemble median indicated a 4% increase in grain yield for doubling $[\text{CO}_2]$, 21% decrease with increasing temperature ($+4^\circ\text{C}$), 1% decrease with increasing rainfall (150% of baseline rainfall) and 17% decrease with decreasing rainfall (50% of baseline rainfall). Nitrogen fertilizer input controlled to a large extent the response to variation in $[\text{CO}_2]$, temperature and rainfall (Figure 4). We describe the interactions between N fertilizer input levels and climate change factors in the subsections below.

3.3.1 | Variations in $[\text{CO}_2]$ and temperature interact with N inputs

The impact of increased $[\text{CO}_2]$ on maize grain yield was smaller when N was limiting (Figure 4). With doubling $[\text{CO}_2]$, the model ensemble median for the grain yield response was smaller with 0 kg N/ha (4% across all sites, i.e. 0.04 t/ha) than with 160 kg N/ha (7% across all sites, i.e. 0.29 t/ha). Model response varied across the sites (Table S4) and ranged between 0% and 5% for 0 kg N/ha, and between 4% and 13% at 160 kg N/ha.

TABLE 3 rRMSE of simulated–observed comparison for six variables of interest for 25 fully calibrated maize models. In bold, models below median sum of ranks for all variables or yield and biomass only. Five models without daily simulation of N dynamics were not ranked

Model class	Model name	rRMSE (%)				Rank					
		Grain yield	Total above-ground biomass	Maximum LAI	Total above-ground plant N	Harvest Index	Soil water	Sum of ranks (all variables)	Sum of ranks (yield and biomass)	Final rank (all variables)	Final rank (yield and biomass)
1	GLAMM	18	31	57	—	32	—	—	—	—	—
	MCWLA	8	41	15	—	32	13	—	—	—	—
2	CELSIUS	12	26	34	—	33	12	—	—	—	—
	SARRA-H	17	31	10	—	34	17	—	—	—	—
	PEGASUS	16	43	79	—	57	78	—	—	—	—
	DNDC	22	34	40	7	21	9	32	20	1	9
3a	STICS	8	26	13	52	23	22	42	6	2	1
	HERMES	23	17	48	26	27	12	43	11	3	4
	DSSAT-IXIM-Maize + Century	20	25	46	28	29	17	47	10	4	3
	APSIM v 7.9	27	27	40	30	31	14	48	18	5	7
	DSSAT-IXIM-Maize + Ceres-SOM	21	28	41	33	29	17	51	15	6	5
	SIMPLACE-Lintlul + Option 2 ^a	11	30	6	43	38	24	54	10	7	2
	MONICA	42	46	11	15	30	18	60	35	8	16
	SALUS	36	48	6	11	41	23	73	35	9	15
	DSSAT-CERES-Maize + Century	34	33	58	52	31	14	75	24	10	10
	MAIZSIM	40	32	41	44	32	22	77	27	11	12
	APSIM v7.10	15	36	41	58	33	26	78	17	12	6
	DSSAT-CERES-Maize + Ceres-SOM	36	35	58	56	32	14	84	27	13	11
	SIMPLACE-Lintlul + Option 1 ^b	42	48	45	30	34	18	85	38	14	18
	EXPERT-N-Sucros	19	36	47	78	39	29	93	20	15	8
3b	RZWQM2	40	54	48	50	41	19	99	37	16	17
	SWB	72	58	37	49	37	43	99	42	17	20
	EXPERT-N-Spass	29	46	43	56	54	32	103	28	18	13
	AGRO-IBIS	82	47	28	51	50	72	104	39	19	19
	EXPERT-N-Ceres	27	67	61	96	41	30	116	33	20	14

Abbreviations: LAI, leaf area index; rRMSE, relative root mean square error.

^aET Hargreaves + heat stress with air temperature.

^bET FAO-56 + heat stress with crop temperature.

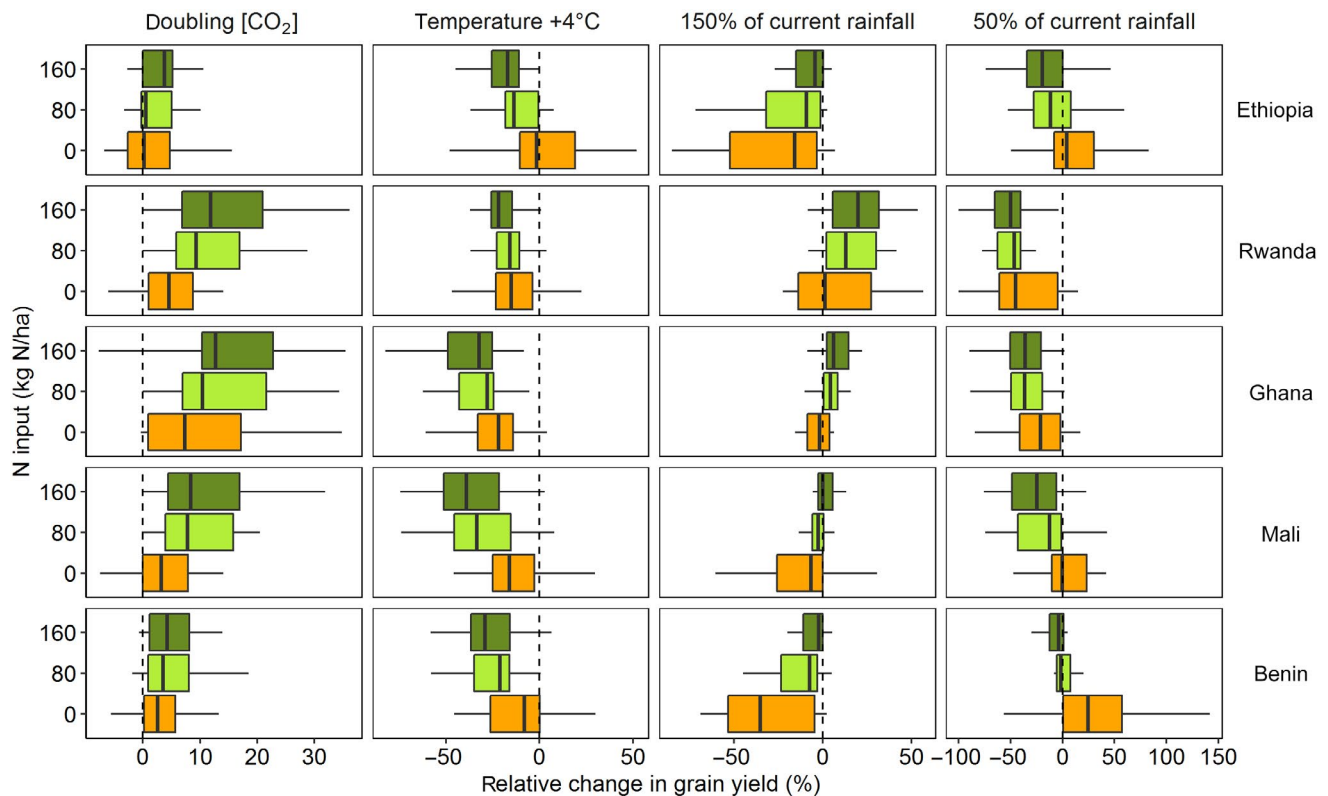


FIGURE 4 Boxplots of relative change in grain yield (compared with baseline climate) when doubling [CO₂], increasing temperature by +4°C, increasing and decreasing rainfall (150% and 50% of baseline) in five sites across sub-Saharan Africa and for three N inputs of 0, 80 and 160 kg N/ha. Simulations are from 24 maize models with full calibration (one model did not perform the sensitivity analysis). Two models not simulating the effect of N on crop growth are displayed only for 160 kg N/ha. The line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below 1.5 interquartile range. Outliers (data points below $Q1 - 1.5 \times (Q3 - Q1)$ or above $Q3 + 1.5 \times (Q3 - Q1)$ where $Q1$ is the first quartile and $Q3$ is the third quartile) were not displayed

Without N fertilization maize grain yield was less affected by higher temperature (+4°C) compared with N fertilization (80, 160 kg N/ha; Figure 4). Across all sites, the ensemble median indicated a 14% and 26% decrease in grain yield as a result of increased temperature with 0 and 160 kg N/ha respectively. The negative effect of higher temperature was stronger at the warm sites (Benin, Mali and Ghana) than at the cool sites (Rwanda and Ethiopia). With 160 kg N/ha, maize grain yield decreased by 29% in Benin, 32% in Ghana and 39% in Mali, and by only 14% in Ethiopia and 16% in Rwanda (Table S4).

Prediction uncertainty, expressed here as the IQR of ensemble relative response in simulated maize yield, was greater for temperature than for [CO₂] variation, without a clear indication that uncertainty decreases with increasing N fertilizer inputs (Figure S5).

3.3.2 | Variation in rainfall in interaction with N inputs

Comparing the effect of N fertilization under conditions of increased rainfall (150% of baseline), grain yields of the 0 N treatment were more negatively affected than those with inputs of 80 or 160 kg N/

ha (Figure 4). Across all sites, the model ensemble median indicated a -8% and 0% change in grain yield caused by increased rainfall at 0 and 160 kg N/ha, respectively. In Ethiopia, Mali and Benin, an increase in rainfall had a strong negative effect on grain yield, and the magnitude of this effect was stronger for low N conditions. The ensemble median indicated a 7% decrease in Mali, a 16% decrease in Ethiopia and a 35% decrease in Benin at 0 kg N/ha, and 0%, -4% and -2% in those countries at 160 kg N/ha (Table S4). In Ghana, and Rwanda, increased rainfall had little effect on grain yield when no N was applied (-2% and +1% relative yield change respectively), while positive effects of increased rainfall occurred with 80 and 160 kg N/ha (6% and 20% yield increase respectively).

Without N fertilization maize grain yield was less affected by a decrease in rainfall (50% of current) than with N fertilization (80, 160 kg N/ha; Figure 4). Across all sites, the model ensemble median indicated a 2% and 27% decrease in grain yield with 0 and 160 kg N/ha respectively. Model response varied across the sites (Table S4). The impact of a decrease in rainfall was lower for Ethiopia and Benin (20% and 4% yield decrease at 160 kg N/ha; Table S4) than for Mali, Ghana and Rwanda (25%, 36% and 50% yield decrease at 160 kg N/ha; Table S4), which is consistent with the fact that Ethiopia and Benin had higher seasonal rainfall (Table 1).

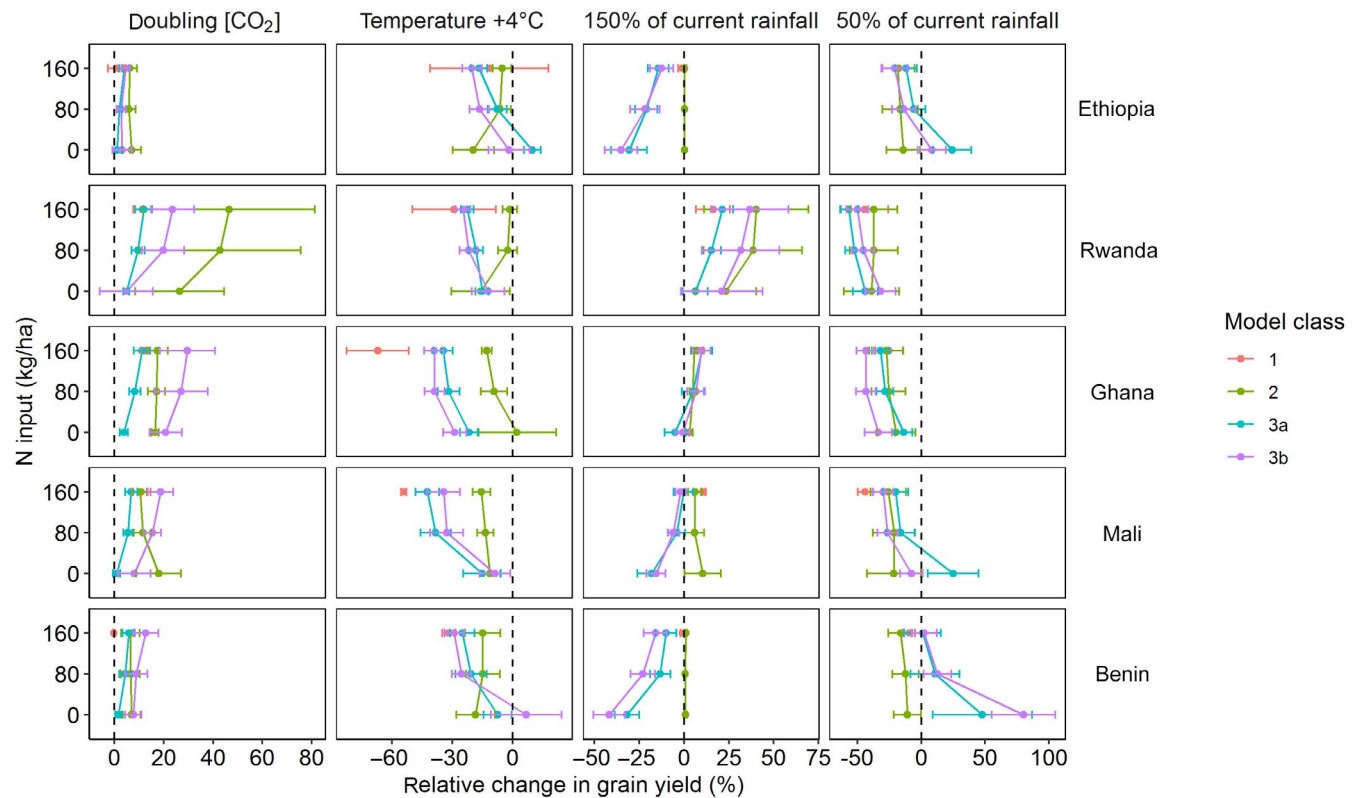


FIGURE 5 Mean ($\pm$ SE) relative change in grain yield (compared with baseline climate) when doubling $[\text{CO}_2]$, increasing temperature by $+4^\circ\text{C}$, increasing and decreasing rainfall (150% and 50% of current) in five sites across sub-Saharan Africa and for three N inputs of 0, 80 and 160 kg N/ha. Simulations are from 25 maize models with full calibration classified in three classes: two models that did not simulate responses to N inputs (class 1, red), three models that simulated response to N inputs but without a daily N module (Class 2, green) and with a daily N module (Class 3). Models below the median sum of ranks for relative root mean square error over all the simulated variables were classified as 'most consistent' models (class 3a, cyan), models above the median as 'less consistent' models (class 3b, purple; see Section 2.3 for a detailed description of the classification). The reader is referred to the web version of this article for interpretation of references to colours

Prediction uncertainty, expressed here as IQR of ensemble relative response in simulated maize yield, for rainfall variation was always higher at low input (0 kg N/ha) than at high N input (80 and 160 kg N/ha) with the exception of Mali for 50% of the baseline rainfall (Figure S5). Decrease in model prediction uncertainty from low to high N input simulations was generally greater for 150% relative rainfall than for 50% decrease in rainfall (Figure S5).

3.3.3 | Impact of model classification on model response to climate change in interaction with N inputs

Classifying the crop models (Table 2) allowed unravelling some of the variability related to the interaction between climate change and N fertilizer inputs. Two models, MCWLA and GLAM (class 1, Table 2), do not simulate responses to N inputs, and hence the interaction between climate change and N input could not be analysed (Figure 5). Three models (PEGASUS, SARRA-H and CELSIUS, see Table 2) simulate a response to N input but do not include a detailed N module. These three models had different responses to climate change and N input

compared with the ensemble model responses described in Sections 3.3.1 and 3.3.2. The simulated response by the SARRA-H model to increased $[\text{CO}_2]$ was higher under the zero N fertilization than under the 80 and 160 kg N/ha fertilization in Mali. The PEGASUS and CELSIUS models simulated very little interaction between increase in $[\text{CO}_2]$ and N fertilization. Similarly, the simulated impact of increased temperature ($+4^\circ\text{C}$) by SARRA-H was largest with the zero N fertilization in Rwanda, Ethiopia and Benin, that is, the opposite of the simulated trend by the model ensemble (see Section 3.3.1). The PEGASUS and CELSIUS models simulated also very little interaction between increase in temperature and N fertilization. The three models (SARRA-H, PEGASUS and CELSIUS) simulated no interaction between 150% of the baseline rainfall and N fertilization. The SARRA-H and PEGASUS models simulated little to no interaction between 50% of the baseline rainfall and N fertilization, while CELSIUS predicted an interaction consistent with the model ensemble behaviour. The response averaged across these three models is shown in Figure 5 (class 2 models).

The magnitude of model responses to some climate change factors was different between class 3a (the 10 most consistent models ranked using all the measured variables) and the 'less consistent' class 3b models (Figure 5). Simulated impact of doubling $[\text{CO}_2]$ was

significantly lower ($p < .05$) for models of class 3a than for those of class 3b. The class 3a models predicted a 0.9% and 5.3% increase in grain yield with doubling $[CO_2]$ at 0 and 160 kg N/ha, respectively, while the class 3b models predicted a 4.0% and 11.8% increase in grain yield. On the other hand, simulated responses to changes in temperature and rainfall did not differ significantly between class 3a and 3b models (Figure 5). When ranked based on grain yield and above-ground biomass only (Table 2), highest ranked models did not differ significantly in their response to $[CO_2]$ and rainfall. The simulated response to increased temperature ($+4^\circ C$) was, however, significantly lower ($p < .05$) for highest ranked class 3a models (considering grain and above-ground biomass) than for the lower ranked class 3b models.

Models of class 3 simulated N leaching, whereas models of the other classes did not. This resulted in a stronger negative impact of increased rainfall on simulated grain yield, especially for zero N fertilization, that is, class 3 models simulated an increase in N leaching with an increase in rainfall (Figure S6). The simulated increase in the amount of N leached with 150% of baseline rainfall did not differ significantly between the model classes 3a and 3b. Models of class 3 explicitly simulated N mineralization unlike the models of the other classes. They, however, did not simulate an increase in N mineralization when temperature was increased (Figure S7).

4 | DISCUSSION

4.1 | Low input systems and model accuracy and uncertainty

Our comparative analysis of model accuracy with partial and full calibration confirms the importance of calibration against observed harvest and in-season variables for accurate simulation of maize growth and yield in smallholder context, as was the case in other model intercomparisons (e.g. Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015). However, rRMSE for grain yield averaged over the fully calibrated models was greater (rRMSE = 26%) for the cropping situations in our study with relatively low inputs than for example, high-input situations in a wheat model intercomparison (rRMSE ~ 10%; Asseng et al., 2013). This confirms our initial hypothesis that model simulations are less accurate for low input and below potential yield situations where soil processes need to be adequately simulated. Model ensembles gave greater accuracy than any model taken at random; in our study an ensemble of at least eight randomly selected models was needed to fall below the typical 13.5% variation of measured grain yields in field experiments. This number is in line with the findings of the previous maize, rice and wheat model intercomparison studies (Asseng et al., 2013; Bassu et al., 2014; Li et al., 2015), and demonstrates the strength of model ensembles. Model ensembles combine models that have complementary strengths in simulated plant and/or soil processes and minimize errors in structure/parameterization that may exist for some processes in individual models.

Model calibration for soil processes appeared to be key for low-input systems. For example, a steep decrease in soil water content occurred during the growing season in the experiments in Rwanda, the site with the lowest seasonal rainfall, and most models were generally able to capture such behaviour. Notably, modelling groups who reported the calibration of specific parameters related to soil water dynamics to match observed soil water, achieved a greater increase in accuracy from partial to full calibration (see Section 3.2.3). A correct simulation of soil mineralization was crucial for accurately simulating maize growth and yield in Benin as no N fertilizer was applied. However, the lack of observations precluded the analysis of model accuracy for N mineralization. The uncertainty in simulated N mineralization was large and not reduced with full calibration, though some models did calibrate the sizes of the organic matter pools and achieved a more accurate simulation of maize N uptake (see Section 3.2.3). As expected, models simulated higher N leaching in the wetter sites (Ethiopia and Benin), but without observations we could not analyse model accuracy with respect to amounts of N leached. The large uncertainty in simulated N leaching was not reduced with full calibration, and only one model reported changes in parameter values related to N leaching with full calibration.

Our model classification indicated that the 'most consistent' models (class 3a; see Section 3.2.3) achieved a greater reduction in RMSE for above-ground plant N after full calibration, hence increasing the likeliness of obtaining accurate simulations that consistently describe the plant growth processes leading to grain yield (Martre et al., 2015). Eventually, the 'most consistent' models simulated grain yield better, that is, with a significantly smaller RMSE compared with 'less consistent' models. Good calibration can, however, be impeded by data availability, for example, above-ground plant N was not measured in Mali, Ethiopia and Rwanda. Due to imbalance in data availability between sites, modellers made assumptions on some inputs and/or model parameters, leading to uncontrolled uncertainty in model simulations. When detailed data on soil is limited, simple models with a limited number of parameters should have an advantage over more complex models (Castañeda-Vera, Leffelaar, Álvaro-Fuentes, Cantero-Martínez, & Mínguez, 2015). Our findings partly supported this argument. Class 3a models all used a simple 'tipping bucket' model approach for water dynamics, suggesting that the more detailed Richards equation for the flow of water in unsaturated soils was not needed to simulate water stress in a satisfactory manner. However, simple models with only one single pool for the simulation of organic matter decomposition and associated N mineralization were not systematically among the 'most consistent' models.

Data quality can also impede good model calibration (Kersebaum et al., 2015), for example, disagreement between (all) model simulations and soil water measurement in Ethiopia in 2013 points to issues with regard to rainfall input data, and/or soil water measurements, and/or errors in the soil textural properties leading to higher predicted water percolation through the soil profile.

4.2 | Low-input cropping systems and climate change impacts

Our study revealed substantial interactions between N input and the effect of climate change. With a doubling in $[\text{CO}_2]$, the model ensemble median for relative grain yield response was +7% across all sites at 160 kg N/ha but only +4% at 0 kg N/ha. Such simulated increase at high N fertilizer input is consistent with the previous maize model intercomparison study that indicated a 7.5% yield increase with doubling $[\text{CO}_2]$ (Bassu et al., 2014). The range of impacts depending on sites was, however, narrower for our study, that is, 4%–13% compared with 0%–19% in Bassu et al. (2014), indicating possible improvements of some models that were used in both studies (Table 2). In addition to a very small yet controversial direct effect of $[\text{CO}_2]$ on C_4 crops photosynthesis (Leakey et al., 2006; Ziska, Sicher, & Bunce, 1999), maize benefits from elevated $[\text{CO}_2]$ because of a 'water-saving effect' (taken into account in the majority of the models, see Table 2) due to reduced stomatal conductance and plant transpiration (Durand et al., 2018). The associated increase in plant growth as a result of this effect requires greater rates of N uptake and assimilation by the plant (Bunce, 2014; Stitt & Krapp, 1999). The maize model ensemble simulated smaller gains from elevated $[\text{CO}_2]$ at 0 kg N/ha than at higher rates (160 kg N/ha), because the beneficial effects of elevated $[\text{CO}_2]$ were constrained by N stress when no fertilizer was applied (Figure 4). Chamber-based and free-air CO_2 enrichment experiments for maize were most often conducted under optimal nutrient supply in temperate climates (Allen, Kakani, Vu, & Boote, 2011; Chun, Wang, Timlin, Fleisher, & Reddy, 2011; Manderscheid, Erbs, & Weigel, 2014). An exception is the study of Bunce (2014) that showed lower maize yield response to elevated $[\text{CO}_2]$ as N fertilization decreased, in line with our model estimates of the impact of elevated $[\text{CO}_2]$ for different N fertilization levels.

When N availability was limiting plant growth under 0 kg N/ha, maize models simulated only minimal impact of higher temperature and reduced rainfall, that is, N stress made climate stresses less prominent. These model results are (a) supported by experimental data showing that crops with low supply of nutrients are less exposed to water stress (Affholder, 1995; Rötter, van Keulen, & Jansen, 1997); and (b) in line with other modelling studies showing a less negative impact of climate variability and change in cropping systems with lower inputs (Affholder, 1997; Faye, Webber, Naab, et al., 2018; Rurinda et al., 2015; Sultan et al., 2014; Traore et al., 2017). The 'Liebig law of the minimum' helps understand such pattern—growth is dictated not by total resources available, but by the scarcest resource (limiting factor). Besides, low nutrient supply causes lower LAI and, therefore, less transpiration compared with crops grown under non-limiting nutrient supply, leading to a lower soil water uptake by the crop and consequently less impact of drought stress when rainfall becomes insufficient (Affholder, 1997; Faye, Webber, Naab, et al., 2018).

An increase in average temperature impacts maize grain yield mainly through a reduced duration of the crop cycle and associated

lower biomass accumulation and thus N uptake, a process well accounted for in current maize models (Bassu et al., 2014). We could not find any experimental work studying possible effects of N supply on crop growth duration. The lower impact of temperature under low N fertilizer input was not due to an increase in N mineralization and soil N availability, because the models did not simulate increased N mineralization under increased temperature (see Section 3.3.3; Figure S7). Although higher temperatures are known to lead to an increase in N mineralization (Gutiérrez, Leirós, Trasar-Cepeda, & Gil-Sotres, 2012), in the model simulations a decrease in topsoil moisture may occur as a result of increased soil water evaporation with increased temperature, thus reducing N mineralization rate and offsetting the increased mineralization due to the rise in temperature.

Maize was more affected by a projected increase in rainfall when N was limiting (0 kg/ha). We attribute this effect to the simulated increase in N leaching with increased rainfall, in line with another modelling report in a smallholder context in West Africa (Freduah et al., 2019). Simulated increase in N leaching with increased rainfall is supported by field experimental studies on tropical soils in Eastern and Southern Africa that observed highest N leaching in growing seasons with highest rainfall amounts (Kamukondiwa & Bergström, 1994; Mapanda, Wuta, Nyamangara, & Rees, 2012; Russo, Tully, Palm, & Neill, 2017).

Overall, the site influenced the impact of climate change. Maize growth and yield in the cooler high altitude sites, that is, Rwanda and Ethiopia, were less affected by increase in temperature, in line with other studies predicting smaller crop yield losses, and in some situations even gains at cooler locations (Bassu et al., 2014; Waha, Müller, & Rolinski, 2013; Zhao et al., 2017). At low N fertilizer inputs, maize at the site with the highest level of soil organic carbon (i.e. Rwanda, see Table 1) was less affected by an increase in rainfall and the associated N leaching, highlighting the crucial role of soil organic matter in the steady provision of N in low-input cropping systems (e.g. Wood, Tirfessa, & Baudron, 2018). Maize yield at sites with higher seasonal rainfall (i.e. Benin and Ethiopia) was less affected by the simulated decrease in rainfall, highlighting the importance of current climate conditions when analysing the impact of climate change (Waha et al., 2013).

We found no evidence that model uncertainty regarding the response to elevated $[\text{CO}_2]$ and temperature would be greater at low levels of N input. However, uncertainty of model response to rainfall change decreased (except in Mali) with the level of N fertilization, indicating that models differed in the way they dealt with this interaction. The high variability in simulated soil N mineralization (see Section 3.2.2) explains to an extent such uncertainties.

4.3 | Influence of model structure on simulated crop responses to climate change

Our analysis of crop model response to climate change coupled with experimental work suggests that accurately accounting for

both N supply and N leaching under different experimental conditions is crucial for modelling climate change impacts on maize growth in SSA. By separating models into classes, we disentangled some of the variability in model response to climate change under contrasting N fertilizer inputs. Most models without a daily N module (models of class 2) did not account for the interactions in the case of increased $[\text{CO}_2]$ and change in rainfall in a way that was consistent with experimental evidence (see Section 3.3 and discussion above). Class 3a models (ranked based on rRMSE for all the observed variables) simulated a smaller impact of elevated $[\text{CO}_2]$ on maize yield irrespective of the N input levels. There were, however, no obvious structural model characteristics differentiating these best models from the others. For light utilization, models using a 'radiation use efficiency' approach or a 'gross photosynthesis-respiration' approach were represented equally within the two classes. Similarly, models with specific formalisms to compute grain number were represented in the two classes. Class 3a models also simulated more accurately crop response to N input than the other models (see Section 3.2.3); therefore, their simulation of the impact of climate change with contrasting N inputs is expected to be more robust. Ranking models based on various plant and soil variables may, however, be disputable since each variable has a different degree of importance for modelling crop growth. For this reason, we investigated an alternative ranking based on grain and biomass yield only. With this approach, the highest ranked models simulated significantly less impact of an increase in temperature irrespective of the N fertilizer level. There were, however, no obvious model structural characteristics differentiating these highest ranked models from the others, for example, for the type of heat stress simulated or the formalism for crop phenology. It should, however, be noted that uncertainty in calibration due to model user subjectivity can sometimes hide the role of specific model structures (Confalonieri et al., 2016). For example, the PHINT parameter (interval between successive leaf tip appearances) in the DSSAT model can be optimized to improve accuracy in LAI and grain yield simulations (Table S3). Whether such optimization without detailed leaf appearance data to calibrate against is a good practice is a point of debate. Identifying highest ranked models prior to simulation is challenging: a given model will often obtain a different ranking for fit to the observations when used with a different data set (i.e. another combination of physical environment and management; Wallach et al., 2018). Without model validation with independent data sets (e.g. Confalonieri, Acutis, Bellocchi, & Donatelli, 2009), it is unlikely that the ranking proposed in this study holds for all possible environments in a smallholder context. The ranking should therefore be seen as a means to understand model behaviour rather than a prescription on which model to use. Eventually, in some cases model response may have been unrealistic, for example, relative grain yield change with doubling $[\text{CO}_2]$ between 50% and more than 100% (i.e. outliers not shown in Figure 4). Systematically discarding models with such unrealistic behaviour could help in model selection and improve ensemble model creation. However, such procedure remains in dispute as

discarding 'extreme' models can lead to overconfidence in models that behave in a similar way, rewarding a convergence that may be the result of similar model assumptions and errors (Knutti, 2010). Analysis of unrealistic behaviour relying on relative changes also deserves caution, as very small values with baseline climate can cause very large relative responses with future climate even if the absolute responses are reasonable.

4.4 | Implications for sustainable intensification in SSA

A substantial proportion of the farm households in SSA face food insecurity (Frelat et al., 2016). Sustainable intensification with increased nutrient inputs and efficient use could drastically increase crop production and improve household food availability, whilst maintaining other important ecosystem services and preventing further land expansion (Loon et al., 2019; Vanlauwe et al., 2014). Our modelling study indicates that farmers intensifying maize production will face a different impact of climate change. With increased N fertilization maize will benefit more from elevated $[\text{CO}_2]$, but will be increasingly negatively impacted as temperature increases and/or if rainfall decreases. The benefits from elevated $[\text{CO}_2]$ in mitigating drought impacts are unlikely to offset negative impacts from changes in temperature and possibly rainfall (e.g. Faye, Webber, Naab, et al., 2018), so that yield penalties and larger yield variability are expected. Increased yield variability may exacerbate the current risk of unfavourable benefit-cost ratio for mineral fertilizer application (e.g. Bielders & Gérard, 2015; Falconnier et al., 2017). Policy interventions aiming at implementing risk coping mechanisms and additional safety nets will therefore be crucial to support sustainable intensification in the context of climate change.

Our findings have implications for developing recommendation domains for specific adaptation strategies. In high rainfall sites like Ethiopia and Benin, nitrate leaching will be further intensified in case of a wetter climate; technologies maximizing N efficiency and preventing losses through leaching, for example, relay intercropping with deep rooting cover crops and split applications of mineral fertilizer, may prove successful. In low rainfall sites like the site in Rwanda, maize will experience more severe drought stress if climate gets drier; drought tolerant cultivars and water-harvesting technologies (e.g. stone lines, tied ridging, zai pits and contour ridging) may help mitigate production losses. Low altitude warm sites (like in Ghana, Mali and Benin) will be more affected by the rise in temperature so that breeding should aim at cultivars adapted to heat stress.

4.5 | Avenues to extend the work

Given the importance of accurately accounting for N dynamics when modelling the response of low-input systems to climate change, further model improvement studies targeting these systems should focus on (a) the evaluation of model ability to accurately simulate soil

organic matter mineralization, soil mineral N dynamics (e.g. leaching), plant N uptake and N stress effects on crop growth by comparing simulations with observed data; and (b) studying the impact of model structure and complexity (e.g. 'tipping bucket vs. Richards equation, number of soil carbon pools, impact of temperature and moisture on soil organic matter mineralization) on the accuracy of model outputs. Comprehensive data sets to perform such analysis currently do not exist for SSA. The research agenda on modelling the effects of climate in low-input conditions should therefore aim at implementing detailed soil-crop monitoring in experiments in contrasting sites representative of SSA. An experimental focus on the interaction between N fertilization and elevated $[\text{CO}_2]$ and temperature will also be required, as models have not been tested against experimental data coming from tropical environments for these interactions. Model sensitivity to rainfall was assessed in this study by assuming a uniform relative change in daily rainfall throughout the growing season. More complex patterns are likely to occur in the future, for example, increase in the frequency and magnitude of intense rainfall events (Taylor et al., 2017), or shortening of the rainy season (Guan et al., 2017). More analyses of model responses that account for these complex patterns are required. Most soils across SSA are highly weathered and inherently poor in P (Buerkert, Bationo, & Piepho, 2001). In three of the five experimental study sites (i.e. Mali, Ghana and Rwanda), substantial amounts of P fertilizer (~25 kg P/ha) were applied, which is considered as sufficient to reach about 70% of the water-limited yield potential (ten Berge et al., 2019; Velde et al., 2014). With such amount of P fertilizer, it is unlikely that P stress was an issue in these sites. For the other sites, accounting for P stress may help to reduce model uncertainty. The number of models able to deal with P stress is, however, limited (e.g. Dzotsi et al., 2010). Although maize is the most important staple food crop in large parts of SSA, other traditional cereals such as sorghum and millet are also widely consumed in West and East Africa (OCDE & FAO, 2016). Other crops such as cassava and banana also contribute substantially to food security in subhumid and humid SSA (OCDE & FAO, 2016). Extending model intercomparisons of climate change impact for these other crops that are often cultivated in environments different from the ones of our study sites would therefore allow for a more comprehensive assessment of diverse smallholder farming systems and food security issues. Besides, climate change is likely to strengthen pest and disease pressure on crops (Deutsch et al., 2018). Although the soil-crop models used in this study do not account for biotic stresses, considering this yield-reducing factor will be a necessary step towards a more integrated assessment of the impact of climate change (e.g. Donatelli et al., 2017) on smallholder farming systems.

5 | CONCLUSION

Our modelling study revealed robust simulated interactions between climate change factors and N fertilization and indicates that maize intensively managed with more N fertilizer will be more sensitive to climate change. Therefore, the needed sustainable intensification of cropping systems in SSA will become

more and more risky as climate changes, which highlights the need for policy interventions aiming at implementing risk coping mechanisms. Predicting the impact of climate change on cropping systems in which N inputs are likely to vary, requires crop models that explicitly account for N stress and N leaching. At least eight fully calibrated models were needed to ensure reasonable accuracy in simulations. Experimental data and model improvements are urgently needed to better evaluate the impact of the interaction between (a) N fertilization and elevated $[\text{CO}_2]$; and (b) N mineralization and elevated temperature. We advocate for a research agenda geared towards filling the current data gap by implementing detailed and comprehensive soil-crop monitoring in contrasting sites representative of agriculture in SSA.

ACKNOWLEDGEMENTS

We are grateful to the members of the AgMIP leadership team for their support and to Senthil Asseng and Pierre Martre for sharing their insights in the AgMIP Wheat Team. The lead author also thanks Sonali McDermid for her help in extracting AgMERRA data.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available from the corresponding author upon reasonable request.

ORCID

Gatien N. Falconnier  <https://orcid.org/0000-0003-3291-650X>
 Marc Corbeels  <https://orcid.org/0000-0002-8084-9287>
 Kenneth J. Boote  <https://orcid.org/0000-0002-1358-5496>
 Myriam Adam  <https://orcid.org/0000-0002-8873-6762>
 Dilys S. MacCarthy  <https://orcid.org/0000-0002-8062-3499>
 Alex C. Ruane  <https://orcid.org/0000-0002-5582-9217>
 Claas Wendel  <https://orcid.org/0000-0001-7608-9097>
 Anthony M. Whitbread  <https://orcid.org/0000-0003-4840-7670>
 Éric Justes  <https://orcid.org/0000-0001-7390-7058>
 Folorunso M. Akinseye  <https://orcid.org/0000-0002-8677-6306>
 Kokou A. Amouzou  <https://orcid.org/0000-0002-4695-4972>
 Saseendran S. Anapalli  <https://orcid.org/0000-0001-5238-1894>
 Christian Baron  <https://orcid.org/0000-0001-9686-9672>
 Bruno Basso  <https://orcid.org/0000-0003-2090-4616>
 Frédéric Baudron  <https://orcid.org/0000-0002-5648-2083>
 Andrew J. Challinor  <https://orcid.org/0000-0002-8551-6617>
 Delphine Deryng  <https://orcid.org/0000-0001-6214-7241>
 Marcelo Galdos  <https://orcid.org/0000-0002-6080-0726>
 Sebastian Gayler  <https://orcid.org/0000-0002-8577-6486>
 Michel Giner  <https://orcid.org/0000-0002-9310-2377>
 Brian Grant  <https://orcid.org/0000-0001-5928-0391>
 Gerrit Hoogenboom  <https://orcid.org/0000-0002-1555-0537>
 Esther S. Ibrahim  <https://orcid.org/0000-0001-8258-0931>
 Bahareh Kamali  <https://orcid.org/0000-0002-8070-0175>
 Kurt Christian Kersebaum  <https://orcid.org/0000-0002-3679-8427>
 Michael van der Laan  <https://orcid.org/0000-0001-8656-623X>
 Louise Leroux  <https://orcid.org/0000-0002-7631-2399>
 Jon I. Lizaso  <https://orcid.org/0000-0002-7612-2560>

- Bernardo Maestrini  <https://orcid.org/0000-0002-9438-0678>
- Elizabeth A. Meier  <https://orcid.org/0000-0003-2394-8120>
- Cheryl H. Porter  <https://orcid.org/0000-0001-7269-6543>
- Eckart Priesack  <https://orcid.org/0000-0002-5088-9528>
- Dominique Ripoche  <https://orcid.org/0000-0003-0785-9953>
- Tesfaye S. Sida  <https://orcid.org/0000-0001-6482-2669>
- Upendra Singh  <https://orcid.org/0000-0001-8653-0333>
- Ward N. Smith  <https://orcid.org/0000-0001-7462-5247>
- Fulu Tao  <https://orcid.org/0000-0001-8574-0080>
- Peter J. Thorburn  <https://orcid.org/0000-0002-6506-0456>
- Dennis Timlin  <https://orcid.org/0000-0003-4883-4664>
- Bouba Traore  <https://orcid.org/0000-0002-4458-6440>
- Tracy Twine  <https://orcid.org/0000-0002-8457-046X>
- Heidi Webber  <https://orcid.org/0000-0001-8301-5424>

REFERENCES

- Affholder, F. (1995). Effect of organic matter input on the water balance and yield of millet under tropical dryland condition. *Field Crops Research*, 41, 109–121. [https://doi.org/10.1016/0378-4290\(94\)00115-5](https://doi.org/10.1016/0378-4290(94)00115-5)
- Affholder, F. (1997). Empirically modelling the interaction between intensification and climatic risk in semiarid regions. *Field Crops Research*, 52, 79–93. [https://doi.org/10.1016/S0378-4290\(96\)03453-3](https://doi.org/10.1016/S0378-4290(96)03453-3)
- Allen, L. H., Kakani, V. G., Vu, J. C. V., & Boote, K. J. (2011). Elevated CO₂ increases water use efficiency by sustaining photosynthesis of water-limited maize and sorghum. *Journal of Plant Physiology*, 168, 1909–1918. <https://doi.org/10.1016/j.jplph.2011.05.005>
- Amouzou, K. A., Lamers, J. P. A., Naab, J. B., Borgemeister, C., Vlek, P. L. G., & Becker, M. (2019). Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. *Field Crops Research*, 235, 104–117. <https://doi.org/10.1016/j.fcr.2019.02.021>
- Amouzou, K. A., Naab, J. B., Lamers, J. P. A., & Becker, M. (2018). CERES-Maize and CERES-Sorghum for modeling growth, nitrogen and phosphorus uptake, and soil moisture dynamics in the dry savanna of West Africa. *Field Crops Research*, 217, 134–149. <https://doi.org/10.1016/j.fcr.2017.12.017>
- Asseng, S., Ewert, F., Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., ... Wolf, J. (2013). Uncertainty in simulating wheat yields under climate change. *Nature Climate Change*, 3, 827–832. <https://doi.org/10.1038/nclimate1916>
- Baron, C., Benjamin, S., Maud, B., Benoit, S., Seydou, T., Thierry, L., ... Michael, D. (2005). From GCM grid cell to agricultural plot: Scale issues affecting modelling of climate impact. *Philosophical Transactions of the Royal Society B: Biological Sciences*, 360, 2095–2108. <https://doi.org/10.1098/rstb.2005.1741>
- Basso, B., Cammarano, D., Troccoli, A., Chen, D., & Ritchie, J. T. (2010). Long-term wheat response to nitrogen in a rainfed Mediterranean environment: Field data and simulation analysis. *European Journal of Agronomy*, 33, 132–138. <https://doi.org/10.1016/j.eja.2010.04.004>
- Bassu, S., Brisson, N., Durand, J.-L., Boote, K., Lizaso, J., Jones, J. W., ... Waha, K. (2014). How do various maize crop models vary in their responses to climate change factors? *Global Change Biology*, 20, 2301–2320. <https://doi.org/10.1111/gcb.12520>
- Bationo, A., Kihara, J., Vanlauwe, B., Waswa, B., & Kimetu, J. (2007). Soil organic carbon dynamics, functions and management in West African agro-ecosystems. *Agricultural Systems*, 94, 13–25. <https://doi.org/10.1016/j.agsy.2005.08.011>
- Bielders, C. L., & Gérard, B. (2015). Millet response to microdose fertilization in south-western Niger: Effect of antecedent fertility management and environmental factors. *Field Crops Research*, 171, 165–175. <https://doi.org/10.1016/j.fcr.2014.10.008>
- Biernath, C., Gayler, S., Bittner, S., Klein, C., Högy, P., Fangmeier, A., & Priesack, E. (2011). Evaluating the ability of four crop models to predict different environmental impacts on spring wheat grown in open-top chambers. *European Journal of Agronomy*, 35, 71–82. <https://doi.org/10.1016/j.eja.2011.04.001>
- Brisson, N., Ruget, F., Gate, P., Lorgeou, J., Nicoullaud, B., Tayot, X., ... Justes, E. (2002). STICS: A generic model for simulating crops and their water and nitrogen balances. II. Model validation for wheat and maize. *Agronomie*, 22, 69–92. <https://doi.org/10.1051/agro:2001005>
- Buerkert, A., Bationo, A., & Piepho, H.-P. (2001). Efficient phosphorus application strategies for increased crop production in sub-Saharan West Africa. *Field Crops Research*, 72, 1–15. [https://doi.org/10.1016/S0378-4290\(01\)00166-6](https://doi.org/10.1016/S0378-4290(01)00166-6)
- Bunce, J. A. (2014). Corn growth response to elevated CO₂ varies with the amount of nitrogen applied. *American Journal of Plant Sciences*, 5, 306–312. <https://doi.org/10.4236/ajps.2014.53042>
- Castañeda-Vera, A., Leffelaar, P. A., Álvaro-Fuentes, J., Cantero-Martínez, C., & Mínguez, M. I. (2015). Selecting crop models for decision making in wheat insurance. *European Journal of Agronomy*, 68, 97–116. <https://doi.org/10.1016/j.eja.2015.04.008>
- Challinor, A. J., Wheeler, T. R., Craufurd, P. Q., Slingo, J. M., & Grimes, D. I. F. (2004). Design and optimisation of a large-area process-based model for annual crops. *Agricultural and Forest Meteorology*, 124, 99–120. <https://doi.org/10.1016/j.agrformet.2004.01.002>
- Chun, J. A., Wang, Q., Timlin, D., Fleisher, D., & Reddy, V. R. (2011). Effect of elevated carbon dioxide and water stress on gas exchange and water use efficiency in corn. *Agricultural and Forest Meteorology*, 151, 378–384. <https://doi.org/10.1016/j.agrformet.2010.11.015>
- Confalonieri, R., Acutis, M., Bellocchi, G., & Donatelli, M. (2009). Multi-metric evaluation of the models WARM, CropSyst, and WOFOST for rice. *Ecological Modelling*, 220, 1395–1410. <https://doi.org/10.1016/j.ecolmodel.2009.02.017>
- Confalonieri, R., Orlando, F., Paleari, L., Stella, T., Gilardelli, C., Movedi, E., ... Acutis, M. (2016). Uncertainty in crop model predictions: What is the role of users? *Environmental Modelling & Software*, 81, 165–173. <https://doi.org/10.1016/j.envsoft.2016.04.009>
- Connolly-Boutin, L., & Smit, B. (2016). Climate change, food security, and livelihoods in sub-Saharan Africa. *Regional Environmental Change*, 16, 385–399. <https://doi.org/10.1007/s10113-015-0761-x>
- Conway, D., van Garderen, E. A., Deryng, D., Dorling, S., Krueger, T., Landman, W., ... Dalin, C. (2015). Climate and southern Africa's water-energy-food nexus. *Nature Climate Change*, 5, 837–846. <https://doi.org/10.1038/nclimate2735>
- Corbeels, M., Chirat, G., Messad, S., & Thierfelder, C. (2016). Performance and sensitivity of the DSSAT crop growth model in simulating maize yield under conservation agriculture. *European Journal of Agronomy*, 76, 41–53. <https://doi.org/10.1016/j.eja.2016.02.001>
- Deryng, D., Conway, D., Ramankutty, N., Price, J., & Warren, R. (2014). Global crop yield response to extreme heat stress under multiple climate change futures. *Environmental Research Letters*, 9, 034011. <https://doi.org/10.1088/1748-9326/9/3/034011>
- Deryng, D., Sacks, W. J., Barford, C. C., & Ramankutty, N. (2011). Simulating the effects of climate and agricultural management practices on global crop yield. *Global Biogeochemical Cycles*, 25. <https://doi.org/10.1029/2009GB003765>
- Descheemaeker, K., Oosting, S. J., Tui, S.-H.-K., Masikati, P., Falconnier, G. N., & Giller, K. E. (2016). Climate change adaptation and mitigation in smallholder crop-livestock systems in sub-Saharan Africa: A call for integrated impact assessments. *Regional Environmental Change*, 16, 2331–2343. <https://doi.org/10.1007/s10113-016-0957-8>
- Deutsch, C. A., Tewksbury, J. J., Tigchelaar, M., Battisti, D. S., Merrill, S. C., Huey, R. B., & Naylor, R. L. (2018). Increase in crop losses to

- insect pests in a warming climate. *Science*, 361, 916–919. <https://doi.org/10.1126/science.aat3466>
- Donatelli, M., Magarey, R. D., Bregaglio, S., Willocquet, L., Whish, J. P. M., & Savary, S. (2017). Modelling the impacts of pests and diseases on agricultural systems. *Agricultural Systems*, 155, 213–224. <https://doi.org/10.1016/j.agsy.2017.01.019>
- Durand, J.-L., Deluska, K., Boote, K., Lizaso, J., Manderscheid, R., Weigel, H. J., ... Zhao, Z. (2018). How accurately do maize crop models simulate the interactions of atmospheric CO₂ concentration levels with limited water supply on water use and yield? *European Journal of Agronomy*, 100, 67–75. <https://doi.org/10.1016/j.eja.2017.01.002>
- Dzotsi, K. A., Jones, J. W., Adiku, S. G. K., Naab, J. B., Singh, U., Porter, C. H., & Gijssman, A. J. (2010). Modeling soil and plant phosphorus within DSSAT. *Ecological Modelling*, 221, 2839–2849. <https://doi.org/10.1016/j.ecolmodel.2010.08.023>
- Falconnier, G. N., Descheemaeker, K., Van Mourik, T. A., Adam, M., Sogoba, B., & Giller, K. E. (2017). Co-learning cycles to support the design of innovative farm systems in southern Mali. *European Journal of Agronomy*, 89, 61–74. <https://doi.org/10.1016/j.eja.2017.06.008>
- FAOSTAT. (2018). *Food and Agriculture Organization of the United Nations, Rome, Italy*. Retrieved from <http://faostat.fao.org>
- Faye, B., Webber, H., Diop, M., Mbaye, M. L., Owusu-Sekyere, J. D., Naab, J. B., & Gaiser, T. (2018). Potential impact of climate change on peanut yield in Senegal, West Africa. *Field Crops Research*, 219, 148–159. <https://doi.org/10.1016/j.fcr.2018.01.034>
- Faye, B., Webber, H., Naab, J. B., MacCarthy, D. S., Adam, M., Ewert, F., ... Gaiser, T. (2018). Impacts of 1.5 versus 2.0°C on cereal yields in the West African Sudan Savanna. *Environmental Research Letters*, 13, 034014. <https://doi.org/10.1088/1748-9326/aaab40>
- Fleisher, D. H., Condori, B., Quiroz, R., Alva, A., Asseng, S., Barreda, C., ... Woli, P. (2017). A potato model intercomparison across varying climates and productivity levels. *Global Change Biology*, 23, 1258–1281. <https://doi.org/10.1111/gcb.13411>
- Folberth, C., Yang, H., Gaiser, T., Abbaspour, K. C., & Schulin, R. (2013). Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. *Agricultural Systems*, 119, 22–34. <https://doi.org/10.1016/j.agsy.2013.04.002>
- Franke, J., Müller, C., Elliott, J., Ruane, A. C., Jagermeyr, J., Balkovic, J., ... Moyer, E. (2020). The GGCM Phase II experiment: Global gridded crop model simulations under uniform changes in CO₂, temperature, water, and nitrogen levels (protocol version 1.0). *Geoscientific Model Development Discussions*, 1–30. <https://doi.org/10.5194/gmd-2019-237>
- Freduah, B. S., MacCarthy, D. S., Adam, M., Ly, M., Ruane, A. C., Timpong-Jones, E. C., ... Adiku, S. G. K. (2019). Sensitivity of maize yield in smallholder systems to climate scenarios in semi-arid regions of West Africa: Accounting for variability in farm management practices. *Agronomy*, 9, 639. <https://doi.org/10.3390/agronomy9100639>
- Frelat, R., Lopez-Ridaura, S., Giller, K. E., Herrero, M., Douchamps, S., Djurfeldt, A. A., ... van Wijk, M. T. (2016). Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proceedings of the National Academy of Sciences of the United States of America*, 113, 458–463. <https://doi.org/10.1073/pnas.1518384112>
- Gaiser, T., Perkons, U., Küpper, P. M., Kautz, T., Uteau-Puschmann, D., Ewert, F., ... Krauss, G. (2013). Modeling biopore effects on root growth and biomass production on soils with pronounced subsoil clay accumulation. *Ecological Modelling*, 256, 6–15. <https://doi.org/10.1016/j.ecolmodel.2013.02.016>
- Guan, K., Sultan, B., Biasutti, M., Baron, C., & Lobell, D. B. (2017). Assessing climate adaptation options and uncertainties for cereal systems in West Africa. *Agricultural and Forest Meteorology*, 232, 291–305. <https://doi.org/10.1016/j.agrformet.2016.07.021>
- Gutiérrez, M. E., Leirós, M. C., Trasar-Cepeda, C., & Gil-Sotres, F. (2012). Effects of moisture and temperature on net soil nitrogen mineralization: A laboratory study. *European Journal of Soil Biology*, 48, 73–80. <https://doi.org/10.1016/j.ejsobi.2011.07.015>
- Holzworth, D. P., Huth, N. I., deVoil, P. G., Zurcher, E. J., Herrmann, N. I., McLean, G., ... Keating, B. A. (2014). APSIM – Evolution towards a new generation of agricultural systems simulation. *Environmental Modelling & Software*, 62, 327–350. <https://doi.org/10.1016/j.envsoft.2014.07.009>
- IPCC. (2013). Annex I: Atlas of global and regional climate projections. In G. J. van Oldenborgh, J. Collins, J. Arblaster, J. Christensen, J. Marotzke, S. B. Power, M. Rummukainen, & T. Zhou (Eds.), *Climate change 2013: The physical science basis. Contribution of working group I to the fifth assessment report of the Intergovernmental Panel on Climate Change* (pp. 1311–1393). Cambridge, UK and New York, NY: Cambridge University Press.
- Jones, J. W., Naab, J., Fatondji, D., Dzotsi, K., Adiku, S., & He, J. (2012). Uncertainties in simulating crop performance in degraded soils and low input production systems. In J. M. Kihara, D. Fatondji, J. W. Jones, G. Hoogenboom, R. Tabo, & A. Bationo (Eds.), *Improving soil fertility recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)* (pp. 43–59). Dordrecht, the Netherlands: Springer. Retrieved from https://doi.org/10.1007/978-94-007-2960-5_4
- Kamukondiwa, W., & Bergström, L. (1994). Nitrate leaching in field lysimeters at an agricultural site in Zimbabwe. *Soil Use and Management*, 10, 118–124. <https://doi.org/10.1111/j.1475-2743.1994.tb00471.x>
- Kersebaum, K. C. (2011). Special features of the HERMES model and additional procedures for parameterization, calibration, validation, and applications. In L. R. Ahuja & L. Ma (Eds.), *Methods of introducing system models into agricultural research* (pp. 65–94). Madison, WI: American Society of Agronomy, Crop Science Society of America, Soil Science Society of America.
- Kersebaum, K. C., Boote, K. J., Jorgenson, J. S., Nendel, C., Bindi, M., Frühauf, C., ... Wegehenkel, M. (2015). Analysis and classification of data sets for calibration and validation of agro-ecosystem models. *Environmental Modelling & Software*, 72, 402–417. <https://doi.org/10.1016/j.envsoft.2015.05.009>
- Kihara, J., Fatondji, D., Jones, J. W., Hoogenboom, G., Tabo, R., & Bationo, A. (Eds.). (2012). *Improving soil fertility recommendations in Africa using the Decision Support System for Agrotechnology Transfer (DSSAT)* (pp. 1–187). The Netherlands: Springer. <https://doi.org/10.1007/978-94-007-2960-5>
- Kim, S.-H., Yang, Y., Timlin, D. J., Fleisher, D. H., Dathe, A., Reddy, V. R., & Staver, K. (2012). Modeling temperature responses of leaf growth, development, and biomass in maize with MAIZSIM. *Agronomy Journal*, 104, 1523–1537. <https://doi.org/10.2134/agronj2011.0321>
- Knutti, R. (2010). The end of model democracy? *Climatic Change*, 102, 395–404. <https://doi.org/10.1007/s10584-010-9800-2>
- Leakey, A. D. B., Uribeharrea, M., Ainsworth, E. A., Naidu, S. L., Rogers, A., Ort, D. R., & Long, S. P. (2006). Photosynthesis, productivity, and yield of maize are not affected by open-air elevation of CO₂ concentration in the absence of drought. *Plant Physiology*, 140, 779–790. <https://doi.org/10.1104/pp.105.073957>
- Li, T., Hasegawa, T., Yin, X., Zhu, Y., Boote, K., Adam, M., ... Bouman, B. (2015). Uncertainties in predicting rice yield by current crop models under a wide range of climatic conditions. *Global Change Biology*, 21, 1328–1341. <https://doi.org/10.1111/gcb.12758>
- Lizaso, J. I., Boote, K. J., Jones, J. W., Porter, C. H., Echarte, L., Westgate, M. E., & Sonohat, G. (2011). CSM-IXIM: A new maize simulation model for DSSAT version 4.5. *Agronomy Journal*, 103, 766–779. <https://doi.org/10.2134/agronj2010.0423>
- Lobell, D. B., Burke, M. B., Tebaldi, C., Mastrandrea, M. D., Falcon, W. P., & Naylor, R. L. (2008). Prioritizing climate change adaptation needs for food security in 2030. *Science*, 319, 607–610. <https://doi.org/10.1126/science.1152339>
- MacCarthy, D. S., Akponikpe, P. B. I., Narh, S., & Tegbe, R. (2015). Modeling the effect of seasonal climate variability on the efficiency of mineral fertilization on maize in the coastal savannah of

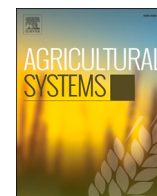
- Ghana. *Nutrient Cycling in Agroecosystems*, 102, 45–64. <https://doi.org/10.1007/s10705-015-9701-x>
- Manderscheid, R., Erbs, M., & Weigel, H.-J. (2014). Interactive effects of free-air CO₂ enrichment and drought stress on maize growth. *European Journal of Agronomy*, 52, 11–21. <https://doi.org/10.1016/j.eja.2011.12.007>
- Mapanda, F., Wuta, M., Nyamangara, J., & Rees, R. M. (2012). Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. *Nutrient Cycling in Agroecosystems*, 94, 85–96. <https://doi.org/10.1007/s10705-012-9528-7>
- Martre, P., Wallach, D., Asseng, S., Ewert, F., Jones, J. W., Rötter, R. P., ... Wolf, J. (2015). Multimodel ensembles of wheat growth: Many models are better than one. *Global Change Biology*, 21, 911–925. <https://doi.org/10.1111/gcb.12768>
- Masvaya, E. N., Nyamangara, J., Descheemaeker, K., & Giller, K. E. (2017). Tillage, mulch and fertiliser impacts on soil nitrogen availability and maize production in semi-arid Zimbabwe. *Soil and Tillage Research*, 168, 125–132. <https://doi.org/10.1016/j.still.2016.12.007>
- Ndoli, A., Baudron, F., Sida, T. S., Schut, A. G. T., van Heerwaarden, J., & Giller, K. E. (2018). Conservation agriculture with trees amplifies negative effects of reduced tillage on maize performance in East Africa. *Field Crops Research*, 221, 238–244. <https://doi.org/10.1016/j.fcr.2018.03.003>
- Nendel, C., Berg, M., Kersebaum, K. C., Mirschel, W., Specka, X., Wegehenkel, M., ... Wieland, R. (2011). The MONICA model: Testing predictability for crop growth, soil moisture and nitrogen dynamics. *Ecological Modelling*, 222, 1614–1625. <https://doi.org/10.1016/j.ecolmodel.2011.02.018>
- Nendel, C., Melzer, D., & Thorburn, P. J. (2019). The nitrogen nutrition potential of arable soils. *Scientific Reports*, 9, 1–9. <https://doi.org/10.1038/s41598-019-42274-y>
- OCDE, & FAO. (2016). Agriculture in sub-Saharan Africa: Prospects and challenges for the next decade. In *OECD-FAO Agricultural Outlook 2016–2025* (pp. 59–95). Paris, France: OECD publishing.
- R Core Team. (2019). *R: A language and environment for statistical computing*. Vienna, Austria: R Foundation for Statistical Computing.
- Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., & Sall, M. (2017). Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. *Agricultural Systems*, 156, 149–176. <https://doi.org/10.1016/j.agsy.2017.05.015>
- Ritchie, J. T., Singh, U., Godwin, D. C., & Bowen, W. T. (1998). Cereal growth, development and yield. In G. Y. Tsuji, G. Hoogenboom, & P. K. Thornton (Eds.), *Understanding options for agricultural production, systems approaches for sustainable agricultural development* (pp. 79–98). Dordrecht, the Netherlands: Springer. Retrieved from https://doi.org/10.1007/978-94-017-3624-4_5
- Rosenzweig, C., Elliott, J., Deryng, D., Ruane, A. C., Müller, C., Arneth, A., ... Jones, J. W. (2014). Assessing agricultural risks of climate change in the 21st century in a global gridded crop model intercomparison. *Proceedings of the National Academy of Sciences of the United States of America*, 111, 3268–3273. <https://doi.org/10.1073/pnas.1222463110>
- Rosenzweig, C., Jones, J. W., Hatfield, J. L., Ruane, A. C., Boote, K. J., Thorburn, P., ... Winter, J. M. (2013). The Agricultural Model Intercomparison and Improvement Project (AgMIP): Protocols and pilot studies. *Agricultural and Forest Meteorology*, 170, 166–182. <https://doi.org/10.1016/j.agrformet.2012.09.011>
- Rötter, R., van Keulen, H., & Jansen, M. J. W. (1997). Variations in yield response to fertilizer application in the tropics: I. Quantifying risks and opportunities for smallholders based on crop growth simulation. *Agricultural Systems*, 53, 41–68. [https://doi.org/10.1016/S0308-521X\(96\)00036-4](https://doi.org/10.1016/S0308-521X(96)00036-4)
- Ruane, A. C., Goldberg, R., & Chrysanthacopoulos, J. (2015). Climate forcing datasets for agricultural modeling: Merged products for gap-filling and historical climate series estimation. *Agricultural and Forest Meteorology*, 200, 233–248. <https://doi.org/10.1016/j.agrformet.2014.09.016>
- Ruane, A. C., Rosenzweig, C., Asseng, S., Boote, K. J., Elliott, J., Ewert, F., ... Thorburn, P. J. (2017). An AgMIP framework for improved agricultural representation in integrated assessment models. *Environmental Research Letters*, 12, 125003. <https://doi.org/10.1088/1748-9326/aa8da6>
- Rurinda, J., van Wijk, M. T., Mapfumo, P., Descheemaeker, K., Supit, I., & Giller, K. E. (2015). Climate change and maize yield in southern Africa: What can farm management do? *Global Change Biology*, 21, 4588–4601. <https://doi.org/10.1111/gcb.13061>
- Russo, T. A., Tully, K., Palm, C., & Neill, C. (2017). Leaching losses from Kenyan maize cropland receiving different rates of nitrogen fertilizer. *Nutrient Cycling in Agroecosystems*, 108, 195–209. <https://doi.org/10.1007/s10705-017-9852-z>
- Sadhukhan, D., Qi, Z., Zhang, T., Tan, C. S., Ma, L., & Andales, A. A. (2019). Development and evaluation of a phosphorus (P) module in RZWQM2 for phosphorus management in agricultural fields. *Environmental Modelling & Software*, 113, 48–58. <https://doi.org/10.1016/j.envsoft.2018.12.007>
- Sida, T. S., Baudron, F., Hadgu, K., Derero, A., & Giller, K. E. (2018). Crop vs. tree: Can agronomic management reduce trade-offs in tree-crop interactions? *Agriculture, Ecosystems & Environment*, 260, 36–46. <https://doi.org/10.1016/j.agee.2018.03.011>
- Smith, W., Grant, B., Qi, Z., He, W., VanderZaag, A., Drury, C. F., & Helmers, M. (2020). Development of the DNDC model to improve soil hydrology and incorporate mechanistic tile drainage: A comparative analysis with RZWQM2. *Environmental Modelling & Software*, 123, 104577. <https://doi.org/10.1016/j.envsoft.2019.104577>
- Stitt, M., & Krapp, A. (1999). The interaction between elevated carbon dioxide and nitrogen nutrition: The physiological and molecular background. *Plant, Cell and Environment*, 22, 583–621. <https://doi.org/10.1046/j.1365-3040.1999.00386.x>
- Sultan, B., & Gaetani, M. (2016). Agriculture in West Africa in the twenty-first century: Climate change and impacts scenarios, and potential for adaptation. *Frontiers in Plant Science*, 7. <https://doi.org/10.3389/fpls.2016.01262>
- Sultan, B., Guan, K., Kouressy, M., Biasutti, M., Piani, C., Hammer, G. L., ... Lobell, D. B. (2014). Robust features of future climate change impacts on sorghum yields in West Africa. *Environmental Research Letters*, 9, 104006. <https://doi.org/10.1088/1748-9326/9/10/104006>
- Tao, F., Palosuo, T., Rötter, R. P., Díaz-Ambrona, C. G. H., Inés Mínguez, M., Semenov, M. A., ... Schulman, A. H. (2020). Why do crop models diverge substantially in climate impact projections? A comprehensive analysis based on eight barley crop models. *Agricultural and Forest Meteorology*, 281, 107851. <https://doi.org/10.1016/j.agrformet.2019.107851>
- Tao, F., Rötter, R. P., Palosuo, T., Díaz-Ambrona, C. G. H., Mínguez, M. I., Semenov, M. A., ... Schulman, A. H. (2018). Contribution of crop model structure, parameters and climate projections to uncertainty in climate change impact assessments. *Global Change Biology*, 24, 1291–1307. <https://doi.org/10.1111/gcb.14019>
- Tao, F., & Zhang, Z. (2010). Adaptation of maize production to climate change in North China Plain: Quantify the relative contributions of adaptation options. *European Journal of Agronomy*, 33, 103–116. <https://doi.org/10.1016/j.eja.2010.04.002>
- Taylor, C. M., Belušić, D., Guichard, F., Parker, D. J., Vischel, T., Bock, O., ... Panthou, G. (2017). Frequency of extreme Sahelian storms tripled since 1982 in satellite observations. *Nature*, 544, 475–478. <https://doi.org/10.1038/nature22069>
- Taylor, S. L., Payton, M. E., & Raun, W. R. (1999). Relationship between mean yield, coefficient of variation, mean square error, and plot size in wheat

- field experiments. *Communications in Soil Science and Plant Analysis*, 30, 1439–1447. <https://doi.org/10.1080/00103629909370298>
- ten Berge, H. F. M., Hijbeek, R., van Loon, M. P., Rurinda, J., Tesfaye, K., Zingore, S., ... van Ittersum, M. K. (2019). Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security*, 23, 9–21. <https://doi.org/10.1016/j.gfs.2019.02.001>
- Traore, B., Descheemaeker, K., van Wijk, M. T., Corbeels, M., Supit, I., & Giller, K. E. (2017). Modelling cereal crops to assess future climate risk for family food self-sufficiency in southern Mali. *Field Crops Research*, 201, 133–145. <https://doi.org/10.1016/j.fcr.2016.11.002>
- Traore, B., van Wijk, M. T., Descheemaeker, K., Corbeels, M., Rufino, M. C., & Giller, K. E. (2014). Evaluation of climate adaptation options for Sudano-Sahelian cropping systems. *Field Crops Research*, 156, 63–75. <https://doi.org/10.1016/j.fcr.2013.10.014>
- Twine, T. E., Bryant, J. J., Richter, K. T., Bernacchi, C. J., McConnaughay, K. D., Morris, S. J., & Leakey, A. D. B. (2013). Impacts of elevated CO₂ concentration on the productivity and surface energy budget of the soybean and maize agroecosystem in the Midwest USA. *Global Change Biology*, 19, 2838–2852. <https://doi.org/10.1111/gcb.12270>
- van der Laan, M., Stirzaker, R. J., Annandale, J. G., Bristow, K. L., & du Preez, C. C. (2010). Monitoring and modelling draining and resident soil water nitrate concentrations to estimate leaching losses. *Agricultural Water Management*, 97, 1779–1786. <https://doi.org/10.1016/j.agwat.2010.06.012>
- van der Velde, M., Folberth, C., Balkovič, J., Ciais, P., Fritz, S., Janssens, I. A., ... Peñuelas, J. (2014). African crop yield reductions due to increasingly unbalanced Nitrogen and Phosphorus consumption. *Global Change Biology*, 20, 1278–1288. <https://doi.org/10.1111/gcb.12481>
- van Loon, M. P., Hijbeek, R., ten Berge, H. F. M., Sy, V. D., ten Broeke, G. A., Solomon, D., & van Ittersum, M. K. (2019). Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Global Change Biology*, 25, 3720–3730. <https://doi.org/10.1111/gcb.14783>
- Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., ... Van Asten, P. (2014). Sustainable intensification and the African smallholder farmer. *Current Opinion in Environmental Sustainability*, 8, 15–22. <https://doi.org/10.1016/j.cosust.2014.06.001>
- Waha, K., Müller, C., & Rolinski, S. (2013). Separate and combined effects of temperature and precipitation change on maize yields in sub-Saharan Africa for mid- to late-21st century. *Global and Planetary Change*, 106, 1–12. <https://doi.org/10.1016/j.gloplacha.2013.02.009>
- Wallach, D., Martre, P., Liu, B., Asseng, S., Ewert, F., Thorburn, P. J., ... Zhang, Z. (2018). Multimodel ensembles improve predictions of crop–environment–management interactions. *Global Change Biology*, 24, 5072–5083. <https://doi.org/10.1111/gcb.14411>
- Whitbread, A. M., Hoffmann, M. P., Davoren, C. W., Mowat, D., & Baldock, J. A. (2017). Measuring and modeling the water balance in low-rainfall cropping systems. *Transactions of the ASABE*, 60, 2097–2110. <https://doi.org/10.13031/trans.12581>
- Wood, S. A., Tirfessa, D., & Baudron, F. (2018). Soil organic matter underlies crop nutritional quality and productivity in smallholder agriculture. *Agriculture, Ecosystems & Environment*, 266, 100–108. <https://doi.org/10.1016/j.agee.2018.07.025>
- Zhao, C., Liu, B., Piao, S., Wang, X., Lobell, D. B., Huang, Y., ... Asseng, S. (2017). Temperature increase reduces global yields of major crops in four independent estimates. *Proceedings of the National Academy of Sciences of the United States of America*, 114, 9326–9331. <https://doi.org/10.1073/pnas.1701762114>
- Ziska, L. H., Sicher, R. C., & Bunce, J. A. (1999). The impact of elevated carbon dioxide on the growth and gas exchange of three C₄ species differing in CO₂ leak rates. *Physiologia Plantarum*, 105, 74–80. <https://doi.org/10.1034/j.1399-3054.1999.105112.x>
- Ziska, L. H., Weerakoon, W., Namuco, O. S., & Pamplona, R. (1996). The influence of nitrogen on the elevated CO₂ response in field-grown rice. *Functional Plant Biology*, 23, 45–52. <https://doi.org/10.1071/pp9960045>

SUPPORTING INFORMATION

Additional supporting information may be found online in the Supporting Information section.

How to cite this article: Falconnier GN, Corbeels M, Boote KJ, et al. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. *Glob Change Biol*. 2020;00:1–23. <https://doi.org/10.1111/gcb.15261>



Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa

Gatien N. Falconnier^{a,b,c,*}, Louise Leroux^{a,b,n}, Damien Beillouin^{d,e}, Marc Corbeels^{a,b,n}, Robert J. Hijmans^f, Camila Bonilla-Cedrez^g, Mark van Wijk^h, Katrien Descheemaekerⁱ, Shamie Zingore^j, François Affholder^{a,b}, Santiago Lopez-Ridaura^k, Eric Malézieux^{d,e}, David Makowski^l, Jairos Rurinda^m, Martin K. van Ittersumⁱ, Bernard Vanlauweⁿ, Ken E. Gillerⁱ, Sabine-Karen Lammoglia^{o,p}, Katharina Waha^q

^a AIDA, Univ Montpellier, CIRAD, Montpellier, France

^b CIRAD, UPR AIDA, F-34398 Montpellier, France

^c International Maize and Wheat Improvement Centre (CIMMYT)-Zimbabwe, 12.5 km Peg Mazowe Road, Harare, Zimbabwe

^d CIRAD, UPR HortSys, F-34398 Montpellier, France

^e HortSys, Univ Montpellier, CIRAD, Montpellier, France

^f Department of Environmental Science and Policy, University of California, Davis, CA, USA

^g Animal Production Systems Group, Wageningen University & Research, Wageningen, the Netherlands

^h International Livestock Research Institute (ILRI), Nairobi 00100, Kenya

ⁱ Plant Production Systems Group, Wageningen University, Wageningen, Netherlands

^j African Plant Nutrition Institute, UM6P Experimental Farm, Benguerir 41350, Morocco

^k International Maize and Wheat Improvement Center (CIMMYT), Apdo, 6-641 06600, México, D.F., Mexico

^l University Paris-Saclay, INRAE, AgroParisTech, UMR MIA 518, 91120 Palaiseau, France

^m Department of Soil Science and Environment, University of Zimbabwe, PO Box MP 167, Mount Pleasant, Harare, Zimbabwe

ⁿ International Institute of Tropical Agriculture, PO Box 30709, 00100 Nairobi, Kenya

^o ABSys, Univ Montpellier, CIHEAM-IAMM, CIRAD, INRAE, Institut Agro, 34060 Montpellier, France

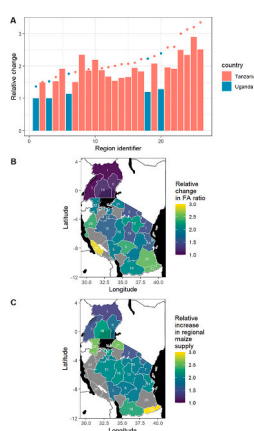
^p CIRAD, UMR ABSys, F-34398 Montpellier, France

^q CSIRO, Agriculture & Food, 306 Carmody Rd, St Lucia, QLD, Australia

HIGHLIGHTS

- Food security analysis with current and profit-maximizing N input in East Africa
- Food secure households are main contributors of national increase in grain supply
- Food insecure households also benefit for their food security
- Variations in maize and fertilizer price impact strongly opportunities to reduce food insecurity

GRAPHICAL ABSTRACT



* Corresponding author at: AIDA, Univ Montpellier, CIRAD, Montpellier, France.

E-mail address: gatien.falconnier@cirad.fr (G.N. Falconnier).

ARTICLE INFO

Editor: Kairisty Topp

Keywords:

Random forest

LSMS-ISA household surveys

Sub-Saharan Africa

ABSTRACT

CONTEXT: Despite recent improvements in living standards, a substantial proportion of farm households in sub-Saharan Africa (SSA) is food insecure, and increasing crop productivity could help address this problem.

OBJECTIVE: We estimated the effect of increasing maize yields with mineral fertilizer on household food security and on regional and national maize supply in two East African countries - Uganda and Tanzania.

METHODS: We estimated maize yield response to nitrogen (N) fertilization with a machine learning model trained on 15,952 observations of maize responses to fertilizer across SSA. Together with spatial price data, we used this model to quantify the profit-maximizing N fertilizer input for a nationally-representative sample of 4188 agricultural households in the two countries. We computed a food availability indicator for all households.

RESULTS AND CONCLUSIONS: The mean profit-maximizing N input was 82 kg/ha in Tanzania, but it was much lower in Uganda (24 kg/ha) mostly because of less favorable prices. The profit-maximizing N input was above the reported N input for 95% of the households in Tanzania and for 43% of the households in Uganda. It was predicted to increase the food availability ratio of food insecure maize growers by 95% in Tanzania, and by 25% in Uganda. The administrative regions where maize supply could increase most were not the same as the regions where the increase in household-level food security was largest. With increased fertilization, food insecure maize growing households (35% in Tanzania and 42% in Uganda) could only contribute about 20% of the overall increase in maize supply, whereas the 20 to 30% food secure households that have a larger area planted with maize could contribute >60%.

SIGNIFICANCE: Our study makes two key contributions: i) a substantial increase in national maize supply is more likely to come from already food secure households with relatively large farms, while food insecure households with small farms may nevertheless increase their household-level food security through maize intensification, and ii) high potential areas to increase maize domestic production do not necessarily match with areas where there is immediate scope to improve household-level food security.

1. Introduction

Over the past decade, living standards have improved substantially in some countries of sub-Saharan Africa (SSA). This has been associated with high growth in agricultural gross domestic product (GDP) (Jayne et al., 2018a), improved health (Masters et al., 2018) and better nutrition (Beal et al., 2017). Despite these positive trends, food security remains a critical issue, and more than a third of rural households across 17 countries in SSA was found to be food insecure (Frelat et al., 2016). Food production has not kept pace with population growth (FAO et al., 2022; Luan et al., 2013) and the majority of countries in SSA are net food importers (Mendez del Villar and Lançon, 2015; Rakotoarisoa et al., 2011; van Ittersum et al., 2016).

Increasing staple food production on current agricultural land is necessary to improve household and national food security, while limiting biodiversity loss and carbon dioxide emissions associated with agricultural land expansion (van Loon et al., 2019; van Ittersum et al., 2016). Yet, crop yields in SSA are much lower than yields that are attainable with good agronomic management practices. A major reason for the low crop yields in SSA is that the average fertilizer use in SSA is low, that is 12, 2 and 3 kg ha⁻¹ for nitrogen (N), phosphorus (P) and potassium (K), respectively (FAOSTAT, 2018). It has, however, rapidly increased in some countries over the past decades (for example, N fertilizer use was 39 kg ha⁻¹ in Zambia and 23 kg ha⁻¹ in Ethiopia in 2018). The limited use of mineral fertilizer leads to widespread nutrient mining (Cobo et al., 2010). Therefore, a significant increase in nutrient inputs in the form of mineral fertilizer is required to sustainably increase crop productivity (ten Berge et al., 2019; Jayne et al., 2013). In combination with mineral fertilizer, the integration of legumes in crop rotations (Franke et al., 2018), the implementation of agroforestry practices (Kuyah et al., 2019), and the better use of organic resources such as manure (Vanlauwe et al., 2014) are key to improve nutrient use efficiency and avoid detrimental nutrient losses to the environment.

The biophysical environment can constrain the effectiveness of mineral fertilizer inputs. For example, fields that are already fertile, or, in contrast, lack secondary nutrients and micronutrients, can be unresponsive to NPK fertilizers (Nziguheba et al., 2021; Vanlauwe et al., 2010). Drought stress or excessive rainfall events can also lead to low fertilizer use efficiency (Affholder, 1997; Mapanda et al., 2012), which may discourage farmers to invest in fertilizer. These biophysical

constraints vary spatially, owing to a combination of natural environmental variability and soil fertility heterogeneity associated with previous field management by farmers (Njoroge et al., 2017). Economic constraints also act as a barrier for investment in fertilizer to increase crop productivity. High prices of fertilizer and low prices of agricultural products can lead to unfavorable cost:benefit ratios (see Jayne et al., 2018 and Bonilla Cedrez et al., 2021 for recent estimates of cost:benefit ratios across SSA). These economic constraints vary spatially, as fertilizer price is usually higher in remote – poorly accessible – areas (Bonilla Cedrez et al., 2020a). In addition, farm household characteristics can constrain intensification of crop production to improve household-level food availability (Tittonell et al., 2010). For example, rural households with limited crop land do not directly benefit from an increase in crop productivity (Giller et al., 2021; Ritzema et al., 2017), and poor households may not have the cash to buy fertilizer, even if it would be profitable to do so. Farmers resource endowment also varies spatially, with local variations as important as country-wide variations (Wichern et al., 2018). The current literature falls short in determining the spatial interaction between biophysical, economic and household-level factors that drive the contribution of maize intensification to food security in the diverse contexts of SSA. In their most optimistic scenario, Ritzema et al. (2017) investigated how a 100% increase in cereal yield would impact household food security of 1700 households in seven countries of East and West Africa. But the increase in cereal yield could be much stronger, e.g. maize yield can be quadrupled in some areas with favorable soil and climate in SSA (<https://www.yieldgap.org/gygaviewer/index.html>). Moreover, the authors relied on site-specific household surveys that possibly did not cover the full span of existing biophysical conditions and farmers' context. Palmas and Chamberlin (2020) investigated the biophysical and economic constraints to the use of mineral fertilizer on maize in Tanzania. Their study brought crucial insights into the spatial determinants of fertilizer profitability, but did not consider the household dimension. Yet, household characteristics (e.g. land per capita) can strongly influence the contribution of intensification of cereal production to improved food security.

Maize is the most important staple food crop in SSA, especially in Eastern Africa (OCDE and FAO, 2016). Tanzania and Uganda are ideal case study countries for several reasons. Firstly, Tanzania and Uganda are in the top-ten maize producing countries in SSA, with 6.2 and 2.7 Mt yr⁻¹ (2017–2018 average), respectively (FAOSTAT, 2018). Secondly,

both countries have diverse agro-ecological conditions allowing the analysis of a wide range of maize growing conditions that also prevail elsewhere across SSA: there are six “maize mega-environments” (Hartkamp et al., 2000) in Tanzania: dry lowland, dry mid-altitude, highland, wet lower mid-altitude, wet upper mid-altitude and wet lowland, and five of these also prevail in Uganda (no wet lowlands). Thirdly, maize yield and fertilizer use in the two countries is low, as it is the case in most countries in SSA: the average maize yield in 2018 was 2.6 t ha^{-1} in Uganda, and 1.7 t ha^{-1} in Tanzania (FAOSTAT, 2018); Nitrogen fertilizer use on cropland was $1.2 \text{ kg (N) ha}^{-1} \text{ year}^{-1}$ in Uganda and $9.1 \text{ (N) kg ha}^{-1} \text{ year}^{-1}$ in Tanzania in 2018 (FAOSTAT, 2018). Fourthly, arable land per capita, a crucial indicator of how agricultural intensification can contribute to improve food security (Giller et al., 2021), is more constrained in Uganda than in Tanzania: land per capita is 0.16 ha in Uganda, close to the first quartile of 0.15 ha for SSA countries, and 0.24 ha in Tanzania, close to the third quartile of 0.25 ha per capita for SSA countries (World Bank, 2021a). Lastly, the two countries allow to explore the impact of variable mineral N fertilizer costs, as these are greater in Uganda than in Tanzania (Bonilla Cedrez et al., 2020a).

In this study we estimate the potential contribution of maize intensification with mineral fertilizer to increase maize production and household food security in Uganda and Tanzania. Using existing datasets across SSA on maize fertilizer trials (Bonilla Cedrez et al., 2021; Kihara et al., 2017; Kihara et al., 2016), fertilizer and maize price (Bonilla Cedrez et al., 2020a, 2020b), and nationally representative household surveys in Uganda and Tanzania (Kilic et al., 2015), we explore the spatial variation in maize response to nutrient inputs, maize prices and fertilizer costs, and household characteristics. We estimate the contribution to national food security, that is, the amount of surplus production that farm households can produce, to be sold and consumed by others. We explore the three following research questions: i) What is the potential increase in household-level food security by intensification of maize production? ii) What is the relative importance of increasing maize production in already food secure and currently food insecure maize growers for national maize production? and iii) Are the regions where household-level food security would benefit most, also the regions where national-level production would increase most? In line with the recent finding that small farms contribute only marginally to global food production (Lowder et al., 2021; Ricciardi et al., 2018), our leading hypothesis was that an increase in national maize production will be achieved mostly by large farms that are already food secure, while food insecure small farms will contribute less to this increase. We also hypothesized that despite their low contribution to national food security, food insecure small farms benefit from maize intensification to improve their food security.

2. Material and methods

2.1. Overall approach

Our study assessed the contribution of the intensification of maize production to food security in three main steps. First, we trained a statistical model with fertilizer trial data to predict maize grain yield responses to N, P and K fertilizer application for the soil and climate conditions prevailing across SSA, and predicted the spatial variation in maize grain yield response to N, P and K fertilizer in Uganda and Tanzania. Then, we computed a simple food security indicator at household level (the food availability ratio, FA, see below) for a nationally representative set of farm households in Uganda and Tanzania. In a last step, we used the predicted maize yield responses to N, and spatial data on fertilizer and maize prices, to estimate i) the profit-maximizing N fertilizer input for each household, ii) the additional maize production from using this amount of fertilizer, and its effect on the household food availability ratio, and iii) the increase in the overall regional and national maize grain supply. We also performed a sensitivity analysis to evaluate the impact of changes in maize prices, N

fertilizer costs, and maize yield responses to N on our estimates.

2.2. Maize yield response to mineral fertilizer

2.2.1. Experimental data from maize fertilizer trials

We combined data from 15,952 maize fertilizer trials conducted at 1352 locations in SSA from 1969 to 2017 (see Appendix 1 in Supplementary materials for details on the composition of the dataset). The dataset included information on trial location (longitude, latitude), maize grain yield, N, P and K fertilizer application rates, topsoil (0–30 cm) characteristics such as soil organic carbon, sand, available P, exchangeable K, Ca and Mg contents and pH, and climate variables such as growing-season rainfall, rainfall intensity and temperature, and number of consecutive dry days over the maize growing season. The trials were rainfed, implying that there may have been water stress in some growing seasons and/or in some locations. Environmental variables that were not reported with the trial data were estimated from spatial data bases (see Appendix 1 in Supplementary materials for details). Soil characteristics varied greatly, allowing the analysis of a wide range of maize growth conditions (Fig. S1). The trial locations spanned all maize-mega-environments (Fig. S2A), and covered a large range of seasonal rainfalls and temperatures (Fig. S2B).

2.2.2. Spatial prediction of maize response to N, P and K fertilizer

We used a Random Forest (RF) algorithm to predict maize grain yield as a function of nutrient inputs (N, P, K), soil properties (soil organic carbon, sand, available P, exchangeable K, Ca and Mg content and pH), and climatic factors (seasonal rainfall, average growing season temperature, number of consecutive dry spell during the season and daily rainfall intensity during the season). We tuned three hyperparameters (parameters that are calibrated during the learning process of the RF algorithm, i.e. the number of trees, the number of candidate predictor variables at each node and the minimum number of samples necessary to split a nonterminal node) based on 70% of the dataset (randomly selected) and an 8-fold cross validation with two replicates. We explored 30 combinations of the hyperparameters obtained by maximizing the coverage of the parameter space. The criterion maximized during the training procedure was the cross-validated proportion of the explained maize yield variance (R^2) averaged over the two replicates. The performance of the best RF model (with optimal combination of hyperparameters) was then evaluated on the 30% hold-out test dataset. Feature analysis (i.e. partial dependence plot and variable importance) was performed on the model fit with the full dataset. Variable importance values were calculated based on a metric that captures the increase in mean squared error (MSE), calculated from out-of-sample predictions, after randomly permuting the values of the respective predictors (Breiman, 2001), using the R package *vip* (Greenwell et al., 2020). Functional relationships between predictors and maize yield were analyzed through partial dependence plots using the *pdp* R package (Greenwell, 2017). A partial dependence plot shows the marginal effect of one input on the model prediction, averaged across the values taken by the other inputs. In order to test the contribution of climate factors, we built one model that included climate variables, and another model that did not include these, and compared the predictive capacity of the two models.

The RF model was then used to predict maize control yield (0 N, 0 P, 0 K) in Uganda and Tanzania at a spatial resolution of 250 m using soil data (topsoil organic carbon, sand, available P, exchangeable K, Ca and Mg content and pH) from Africa SoilGrid (Hengl et al., 2015, 2017). Effects on yield of incremental additions of N (i.e. 20, 40, 60, 80, 100, 120, 160, 180 and 200 kg ha^{-1}) were then investigated. Though the model was built to deal with the interactions between N, P and K inputs, for this spatial exploration we focused on the impact of N and assumed for all N additions an input of 20 kg ha^{-1} of both P and K, i.e. the P and K amounts that a compound basal fertilizer application would bring.

2.3. Food security analysis

2.3.1. Farm household survey data

We used the Living Standard Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA) of 2010–2011 for Uganda and Tanzania (Kilic et al., 2015). These household surveys are nationally representative and cover the main regions of Uganda (World Bank, 2021b) and Tanzania (World Bank, 2021c). These surveys included 2716 households in Uganda and 3440 in Tanzania. Households reporting no crop production and households with missing location coordinates were excluded from the analysis, leading to a reduced sample of 1753 farm households in Uganda and 2435 in Tanzania. We used the following variables: household location (with a 10-km offset), household composition, farmer-reported total cropped land and area for the different crops, farmer-reported total crop production and sales of crop production, mineral fertilizer use on crops, total livestock production (meat and milk), sales of livestock products, and off-farm income.

2.3.2. Food security indicator: the household-level food availability ratio

We adopted the food security indicator described in Frelat et al. (2016), also used in Ritzema et al. (2017), Wichern et al. (2017) and Wichern et al. (2019): the ratio of household-level food availability (expressed in potential food equivalent energy, kcal per day) to household energy need (in kcal per day). Household-level food availability was computed as the sum of (i) the energy from crop and livestock products consumed by the household and (ii) the energy that could be obtained from food purchases with the income earned with the sales of on-farm products (crop and livestock) and off-farm activities. Consumption of on-farm grown crop and livestock products was computed by subtracting the reported sold quantities from the reported produced quantities. Energy in consumed crop and livestock products was then computed using product-specific energy content. In order to compute (potential) household-level food availability, the income from the sales of on-farm products and from off-farm activities was converted into energy (assuming that all of it was used to purchase maize) and added to calories in consumed crop and livestock products produced on-farm. Household energy need was obtained by multiplying household size (expressed in adult male equivalent) with the assumed 2500 kcal d⁻¹ energy need of a male adult (FAO, 2001). The food availability ratio was computed as the ratio of household-level food availability to household energy need. A food availability ratio of one indicates that potential calorie availability at household level (on-farm production plus the calories that could be obtained with the income from off-farm activities and sales of farm products) matches household needs. The food availability ratio corresponds to potential food availability, i.e. in reality households do not entirely use their on- and off-farm income to purchase the staple food (maize in our case), because of other consumptive needs and also dysfunctional markets (Dillon and Barrett, 2017). It therefore quantifies the *potential* of a household to be food secure. Under land, market and/or production constraints, the food availability ratio has been shown to be well correlated to other food security indicators (Hammond et al., 2017), namely the Household Dietary Diversity Score (HDDS), the Household Food Insecurity Access Scale (HFIAS) (Coates et al., 2007) and the number of months in which households experience food insecurity (van Wijk et al., 2020). The food availability ratio increased with HFIAS and HDDS, up to a food availability ratio of two (Hammond et al., 2017). A food availability ratio of two indicates that potential calorie availability at household level is twice household needs. We considered households with a food availability ratio below two as “food insecure”, and those with a food availability ratio above two as “food secure”. We further classified households with a food availability ratio below one as “food deficient households”, and those with a food availability ratio between one and two as “food fragile households”. Depending on whether households cultivated maize (i.e. maize area on the farm above zero) or not, they were subsequently classified into “food insecure maize growers” and “food insecure

non-maize growers”.

In previous studies, farmer-reported maize yield was used to quantify the food availability indicator in Uganda and Tanzania (e.g. Wichern et al., 2017; Fraval et al., 2019). For our analysis we used the maize yields predicted by the model for the N, P, K application reported by the farmer in the survey. Fields with missing information on N, P and K inputs, that is, for 99 fields in Uganda (out of 3603 surveyed fields) and 844 fields in Tanzania (out of 2125 surveyed fields), were assumed to have received median mineral fertilizer application (of all informed fields per country), which was zero in Tanzania and Uganda. Wichern et al. (2017) and Fraval et al. (2019) used the median of the reported maize prices per region to calculate the income from sold maize. In this study, we used the spatially interpolated maize price as in Bonilla Cedrez et al. (2020b). Similar to the farmer-reported prices in the LSMS surveys, they were higher in Tanzania than in Uganda (Fig. S3A, Fig. S4).

2.3.3. Computing profit-maximizing N input

Using the N response predicted by the RF model at the household locations, we computed the partial gross margin (i.e. not including the cost of other inputs that are left unchanged) for incremental additions of fertilizer N: 20, 40, 60, 80, 100, 120, 160, 180 and 200 kg ha⁻¹:

$$gm_i = (Y_{0N} + NAE_i \times i) \times \text{maize price} - i \times N \text{ cost} \quad (1)$$

where gm_i is the gross margin for N input rate i , Y_{0N} is maize grain yield with no N fertilizer input predicted by the model at a given household location, $N-AE_i$ is the agronomic efficiency of N predicted by the model at a given household location, i is the N input rate, *maize price* is the predicted maize price at a given household location, and *N cost* is N fertilizer cost at a given household location. Profit-maximizing N input was the N input rate with the highest gross margin at a given household location. Additional labor cost for increased fertilizer application was not considered because of lack of reliable data.

N-AE was computed as follows (Vanlauwe et al., 2011):

$$NAE_i = \frac{(Y_i - Y_{0N})}{i} \quad (2)$$

where Y_i is the maize grain yield with N input rate i and Y_{0N} is the maize grain yield with no N fertilizer input.

The market maize price and N fertilizer cost at a given household location was extracted from the spatial dataset of Bonilla Cedrez et al. (2020a, 2020b) (Appendix 2 in Supplementary materials describes the model development procedure of these two studies).

2.3.4. Change in food availability ratio and increase in regional and national maize supply

When profit-maximizing N fertilizer input was above the currently reported N fertilizer input by farmers, we computed the corresponding potential additional maize production ΔP :

$$\Delta P = (Y_{new1} - Y_{current1}) \times \text{area}_{s1} + (Y_{new2} - Y_{current2}) \times \text{area}_{s2} \quad (3)$$

where Y_{new1} and Y_{new2} are the predicted maize yields with profit-maximizing N input for the short and long growing seasons, respectively, $Y_{current1}$ and $Y_{current2}$ are the corresponding predicted maize yields with the N input as reported by the farmer in the survey, and area_{s1} and area_{s2} are the maize areas in, respectively, short and long season, as reported by the household head in the survey (depending on household location, there may be only one growing season and area_{s2} was therefore equal to 0). We assumed equal maize responses to N for the two seasons at a given household location. When profit-maximizing N fertilizer input was equal or below the currently reported N fertilizer input, ΔP was set to 0. ΔP was converted to energy and used to compute the household food availability ratio adjusted for the use of profit-maximizing N input (FAprofmax). A relative change in the household food availability ratio (ΔFA) was then computed as follows:

$$\Delta FA = FA_{\text{profitmax}} / FA_{\text{baseline}} \quad (4)$$

Where $FA_{\text{profitmax}}$ is the food availability ratio with profit-maximizing N input and FA_{baseline} is the food availability ratio with current reported N input on maize.

The impact of N-AE and farm characteristics (per-capita maize area, total cropland, livestock and off-farm income) on ΔFA was explored by classifying farms in three classes with regard to these variables: class one below the 33th percentile of all farms for the considered variable, class two between the 33th and 66th percentile, and class three above the 66th percentile.

Then ΔP was aggregated for all surveyed household at the level of the administrative region and country, to compute the relative increase in maize grain supply, assumed to be a proxy for the relative increase in regional/national maize production. The contribution of food insecure and food secure households (further disaggregated by classes of per-capita maize area) to this potential increase in maize grain supply was also calculated.

2.3.5. Sensitivity analysis

The impact of variations in N-AE, maize price and N cost on i) the profit-maximizing N input, ii) the share of food insecure maize growers who would increase their food availability ratio with the use of profit-maximizing N input, iii) the median ΔFA of food insecure maize growers, and iv) the relative potential increase in national maize grain supply, was explored through sensitivity analysis. N-AE, maize price and N fertilizer cost varied between 0.25 and 2 times their baseline value.

3. Results

3.1. Maize grain yield predictions

The inclusion of climate-related predictors (seasonal rainfall and mean temperature over the maize growing season, number of consecutive dry days over the season, and daily rainfall intensity over the season) only marginally improved the predictive capacity of the model; R^2 increased from 0.82 to 0.87. For this reason, we used the RF model without climate variables. The model predicted maize grain yield (for hold-out data) with a Root Mean Square Error (RMSE) of 919 kg grain yield ha^{-1} (corresponding to a relative RMSE of 27%), and a Mean Absolute Error (MAE) of 657 kg grain yield ha^{-1} (Fig. 1). Uncertainty in model predictions increased with higher values of observed maize yield (Fig. 1). N and P fertilizer inputs contributed most to predict maize yield, followed by the soil sand content (Fig. S5). In contrast, the contribution of K fertilizer and that of the other soil properties (available P, exchangeable K, Mg, Ca, organic carbon and pH) was marginal (Fig. S5). Predicted maize yield increased with N applied in the range 0–150 kg N ha^{-1} and with P up to 50 kg P ha^{-1} , but decreased with coarser soil texture (higher soil sand content, Fig. S6).

3.2. Predicted maize yield in response to fertilizer in Uganda and Tanzania

Predicted maize grain yields with no fertilizer input (“control yield”) ranged from 500 to >2500 kg/ha (Fig. 2A). Predicted control yield was generally smaller in sandy areas such as the coastal areas in Tanzania and somewhat higher in areas with high soil available P such as the volcanic soils in Eastern Uganda near Mount Elgon and in the northern highlands of Tanzania near Kilimanjaro (Figs. S7, S8). With the maximum fertilizer use considered (200 kg N ha^{-1} , 20 kg P ha^{-1} , 20 kg K ha^{-1}), predicted yield increased by up to five times the control yield (Fig. 2B). The largest predicted yield increase was in areas with the smallest control yields (for example, in the southwest Tanzanian highlands, south-eastern Tanzania, and the area around Lake Victoria in Uganda). Median N-AE (across locations) was 20 kg (grain) kg (N) $^{-1}$ with N inputs of 40 kg/ha, and decreased gradually with higher N

fertilizer inputs (Fig. S9B). N-AE also significantly (P -value <0.001) decreased with higher control yields, lower sand content, and higher soil organic carbon (Fig. S10). As a consequence, the areas with the lowest control yields were generally areas of highest N-AE (Fig. 2A and Fig. S11).

3.3. Food security analysis with current fertilizer use

Fertilizer use reported by farmers in the 2011 survey was very low. In Tanzania, only 12% of the 3212 surveyed maize plots had received N, 3% had received P and 0.3% had received K, with a median application (for fields receiving mineral fertilizer) of 38 (N), 12 (P) and 7 (K) kg ha^{-1} . In Uganda, <1% of the 3553 surveyed maize plots had received mineral fertilizer, with median application of 1.0 (N), 1.4 (P) and 2.5 (K) kg ha^{-1} . Overall, predicted maize grain yield (with N use reported by farmers) was greater (median = 1207 kg ha^{-1}) than farmer-reported maize yield (median = 482 kg ha^{-1}), possibly because of weed/disease/pest stresses not accounted for by the RF model. Yet, in some cases, especially in Uganda, farmer-reported yield was greater than the predicted yield with the reported N use – possibly because of the uncertainty related to farmers’ estimates of their maize production and area.

We found that a large share of the surveyed farm households was food insecure when using the maize yield predicted with their reported N use: 44% of the households in Tanzania and 46% in Uganda had a food availability ratio of less than two, and 25% of household in Tanzania and Uganda had a food availability ratio of less than one (Fig. 3). When using farmer-reported maize yield, these percentages were greater in Tanzania, and similar in Uganda: 74% of the households in Tanzania and 45% in Uganda had a food availability ratio of less than two. In what follows we report results that used predicted maize yields. Crops produced and consumed on-farm were the largest contributors to household food availability for food insecure ($FA < 2$) households in Tanzania (Fig. 3a). Off-farm income and sales of livestock and crop products contributed more to the food security status of farm households in Uganda than in Tanzania (Fig. 3b). The majority of food insecure ($FA < 2$) households produced maize: 64% in Tanzania and 51% in Uganda. The majority of food secure ($FA > 2$) households also grew maize, 87% in Tanzania and 58% in Uganda. There were no obvious spatial patterns

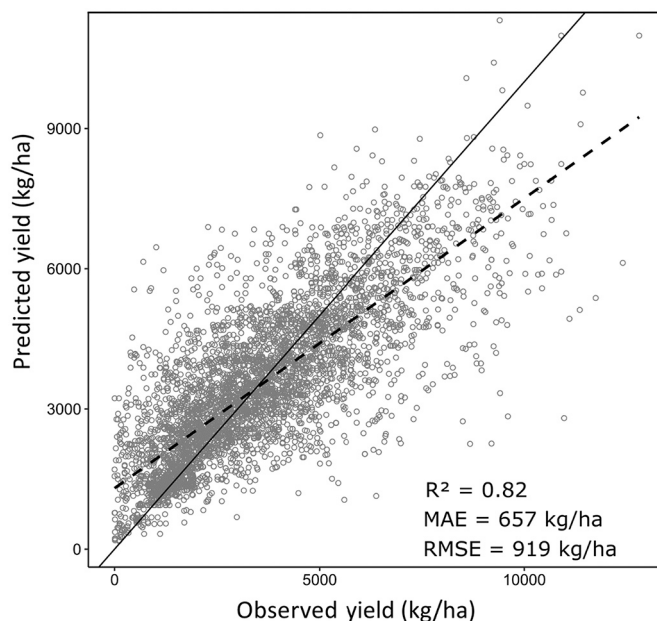


Fig. 1. Observed and Random Forest predictions of maize yield for the maize trials across sub-Saharan Africa used for model validation. The solid line is the 1:1 line, the dotted line is the regression line of predicted vs observed values.

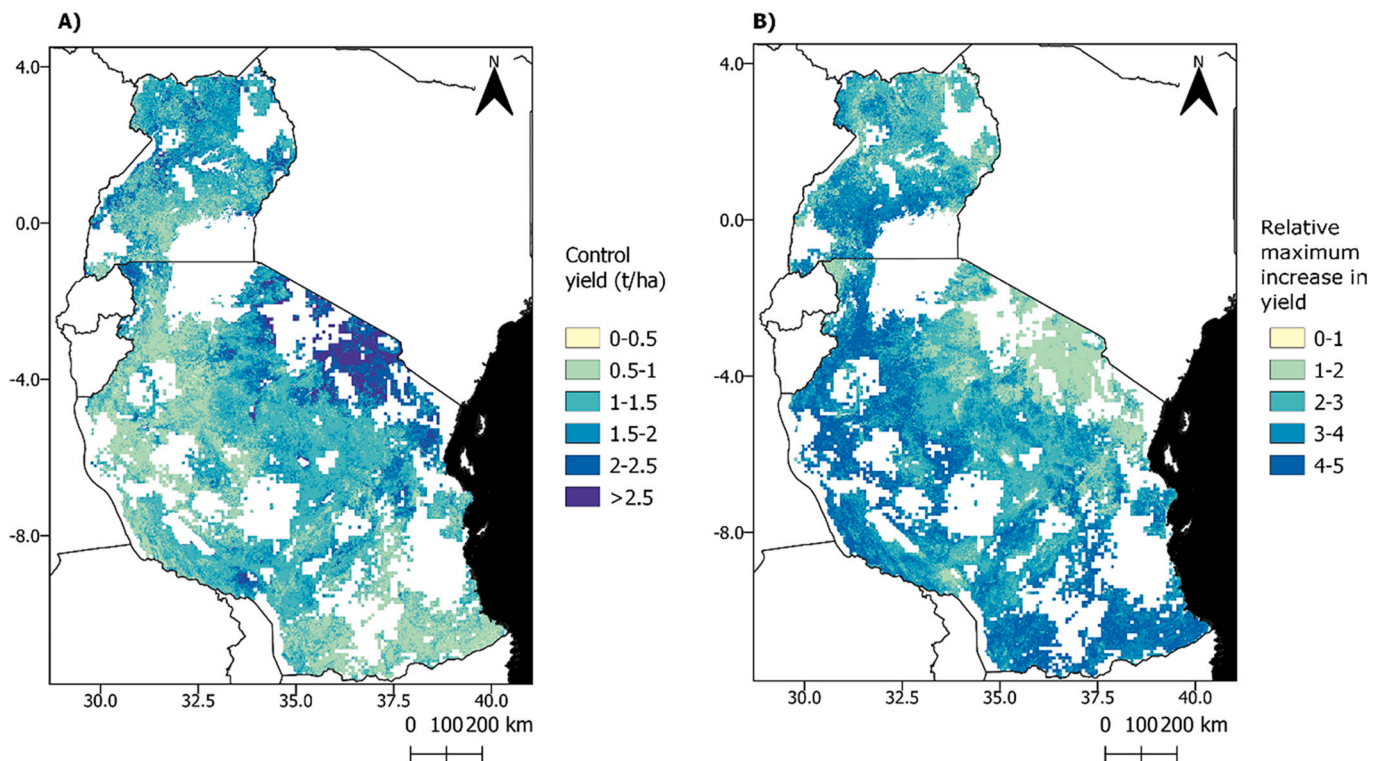


Fig. 2. A) Control maize yield (no fertilizer input) predicted by the Random Forest model and B) maximum relative increase in yield (i.e. yield with maximum (200 N/20P/20 K) fertilizer application divided by control yield). Areas in Uganda and Tanzania where maize is not grown (according to IFPRI, 2020) appear in white. In areas with two (short and long) cropping seasons per year, the model predicted the same yield because weather-related variables were not used as input to the Random Forest model.

in the locations of food insecure maize growers; Households were sampled and surveyed in the eastern, western, northern and southern parts of Uganda and Tanzania (Fig. S12A), and food insecure maize households could be found in almost all regions where the survey was conducted (Fig. S12B). The scope for intensifying maize production (that is, the maximum relative increase in maize yield, Fig. 2B) varied greatly across the locations where food insecure households were found, in both countries (Fig. S12B).

3.4. Impact of additional N input on household food security

Based on model prediction and spatial price data, the mean profit-maximizing N input was 82 kg (N) ha⁻¹ in Tanzania, and only 24 kg (N) ha⁻¹ in Uganda (Fig. S13). The difference between countries was mostly attributed to lower maize price and higher N cost in Uganda (Fig. S4). For 90% of maize growers in Tanzania (95% of the food insecure maize growers), profit-maximizing N input was above the current reported N use, and their food availability ratio was predicted to increase when using the profit-maximizing N input. In Uganda, this was the case for only 41% of the maize growers (43% of the food insecure maize growers). Households for which profit-maximizing N input was above current reported use were spread all over Tanzania, and in Uganda around Lake Victoria (Fig. S13B), i.e. in areas with higher maize prices, lower fertilizer costs, and thus with a maize price: N fertilizer cost ratio compatible with profitable use of more fertilizer (Fig. S3).

The relative increase in the food availability ratio (with additional N input) decreased with the baseline food availability ratio: food insecure (FA > 2) households benefited much more in relative terms, than food secure (FA < 2) households (Fig. 4A). In addition, household with greater N-AE, larger per-capita maize area, and larger cropped land benefited most from the use of profit-maximizing N inputs (Fig. 4B, C and D). Off-farm and livestock income had only a marginal impact on the relative increase in food availability ratio (Fig. 4E and 5F).

With the additional - profit-maximizing - N input, the share of food insecure maize growers was predicted to drop from 28% to 13% of the total household population in Tanzania (Fig. 5A). In Uganda, the change was marginal, i.e. from 23% to 21% (Fig. 5A). The farm households who could reach food security had medium to large per-capita maize area (above 0.17 ha in Tanzania, and 0.03 ha in Uganda) (Fig. 5B). None of the households with small per-capita maize area could achieve food security with the additional profit-maximizing N input (data not shown).

3.5. Regional-level vs household-level food security

Though food insecure (FA < 2) households benefited more from profit-maximizing N input for their food security than food secure (FA > 2) households, they contributed only marginally to the overall increase in national maize supply. Food insecure households contributed <20% to the overall increase in maize supply in Tanzania and Uganda, though they represented around 40% of the total farm population in both countries (Fig. 6). In contrast, food secure households with large per-capita maize area, contributed >60% to the overall increase in maize supply in both countries, though they represented only 20 to 30% of total household population (Fig. 6).

The relative increase in regional maize supply with N fertilizer use was predicted to vary between one (i.e. no increase) and three, across administrative regions in Tanzania and Uganda (Fig. 7A). In some regions, this increase in total maize production concurred with an increase in the household-level food availability ratio for food insecure maize growers. For example, in the Mtwara Region in southern Tanzania (#23 in Fig. 7), regional maize supply was predicted to increase three times, and the food availability ratio for food insecure households by almost 2.5 times. However, there were regions where despite a small predicted increase in total maize supply, the predicted increase in household-level food availability for food insecure maize growers was substantial. For example, in the Iringa Region in central Tanzania (#8 in Fig. 7), total

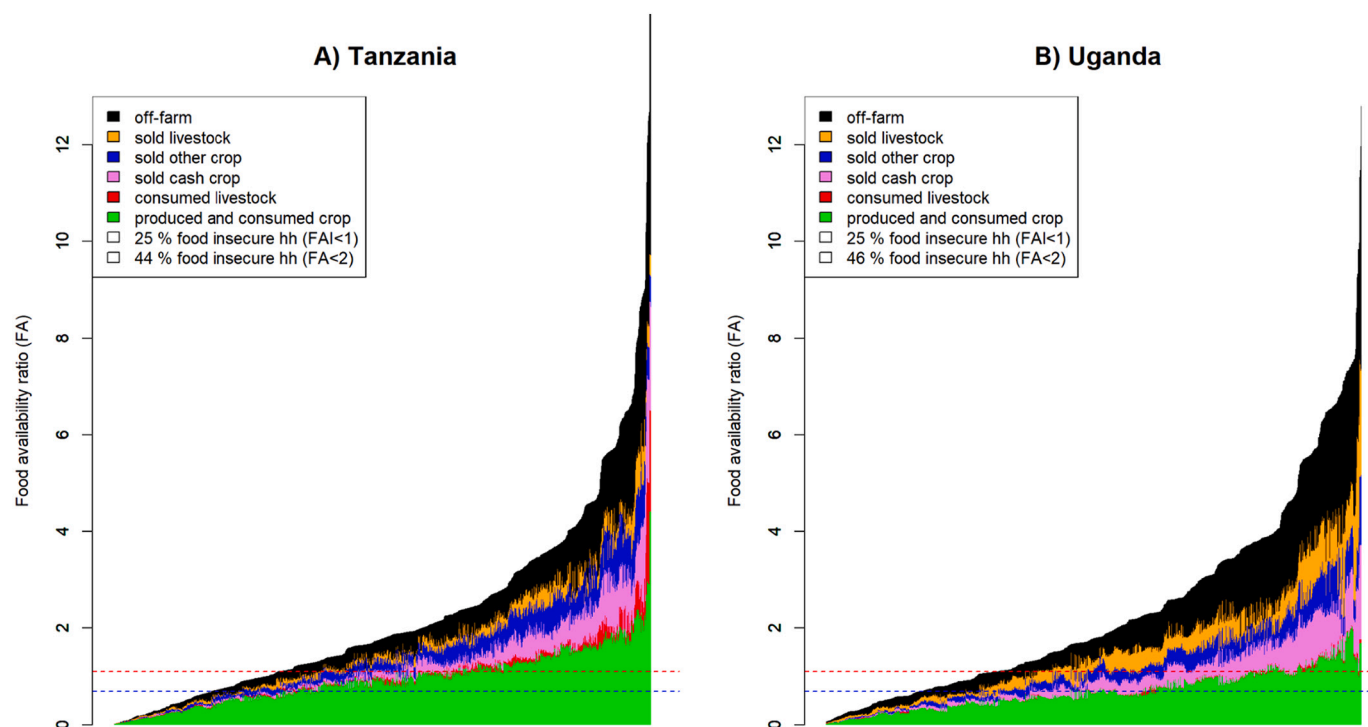


Fig. 3. Household (hh) food availability ratio (FA) for 2435 households in Tanzania (A) and 1753 households in Uganda (B). The y-axis was log-transformed so that $y = \log(FA + 1)$. Households were ordered by increasing food availability ratio (i.e. the ratio of available food to the required food) along the x-axis. A bar is one household. The red dashed line is the 5000 kcal $\text{cap}^{-1} \text{day}^{-1}$ food security threshold (i.e. food availability ratio = 2), and the blue dashed line is the 2500 kcal $\text{cap}^{-1} \text{day}^{-1}$ food security threshold (i.e. food availability ratio = 1). A rolling average was applied with subsets of 30 households to smooth the curves for easier interpretation. Different colours indicate the source of the food, be it produced on-farm or purchased. Crops were considered as cash crops when $>90\%$ of the annual production was sold. Large values of sold and consumed crop on the right side of the plots correspond to potential bias in survey data rather than to real consumption values. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

maize supply was predicted to increase 1.8 times, while the household-level food availability ratio for food insecure maize growers was predicted to increase 2.3 times. Regions where the potential for increasing total maize supply was highest did not necessarily match with regions with the largest potential for improving household-level food security.

3.6. Impact of changes in N-AE, maize price and N fertilizer cost

The profit-maximizing N input, the share of beneficiaries (i.e. food insecure maize growers who increased their food availability ratio with additional N fertilizer use on maize), and the relative national increase in maize supply were all sensitive to changes in maize prices, N-AE and N fertilizer costs (Fig. 8). Changes in N-AE had the same effect as changes in maize prices on the output variables of Fig. 7, which is not surprising as both variables play a similar role in the equation that determines profitability of N fertilizer use (see Section 2.3.3). On the other hand, the median relative change in food availability ratio for food insecure maize growers was not sensitive to changes in maize prices, N-AE and N fertilizer costs, because it was also influenced by the share of beneficiaries (i.e. this share fluctuated in the different scenarios on maize prices and N fertilizer costs) (Fig. 8C).

4. Discussion

4.1. Potential and obstacles of maize intensification to improve household food security

Our analysis showed that a substantial share of food insecure maize growers in Tanzania and Uganda could increase their household food availability in the short term with additional N fertilizer use on maize. This finding matches the results of an analysis in East, West and

Southern Africa (comprising 1024 households in total) of Giller et al. (2021), who estimated that closing the yield gap of major crops would allow $>50\%$ of farm households to become food secure.

Soil properties influence the opportunity for farm households to improve their food security. Largest benefits were obtained in areas with large N-AE values, that is, on sandy soils with low soil organic matter and therefore low maize yields when no fertilizer was used. On the other hand, smaller N-AE values were achieved on clayey soils on which maize yields in the absence of fertilizer were relatively high because these soils tend to have more organic matter that can mineralize and provide substantial amounts of N to the crop in the absence of fertilizer. Some characteristics of the farm households were also important in enhancing food security at household level. We found that the opportunity to achieve food security through intensified fertilizer use increased with farm size and maize area per capita, similar to the findings of Giller et al. (2021) for small farms sizes in Ethiopia, Ghana and Malawi. However, in addition to intensification of crop production, off-farm income is key for enhanced food security at household level. Agricultural intensification may, however, help spur a thriving rural non-farm economy that can generate alternative income sources for households (Haggblade et al., 2010). In this context, rural to urban migration, the so-called “natural Malthusian population control” (Demont et al., 2007) can restrain further farm fragmentation in rural areas and provide at the same time key remittances for the development of the rural economy.

Although additional N fertilizer use could substantially contribute to improved household food security, this strategy was not profitable for farm households in locations where the maize price and N fertilizer cost were unfavorable; the estimated profit-maximizing N input was null in Western, Northern and Eastern Uganda in particular, corroborating the low current use of mineral fertilizer by farmers. An increase in the price: cost ratio could be achieved with input subsidy programs for maize

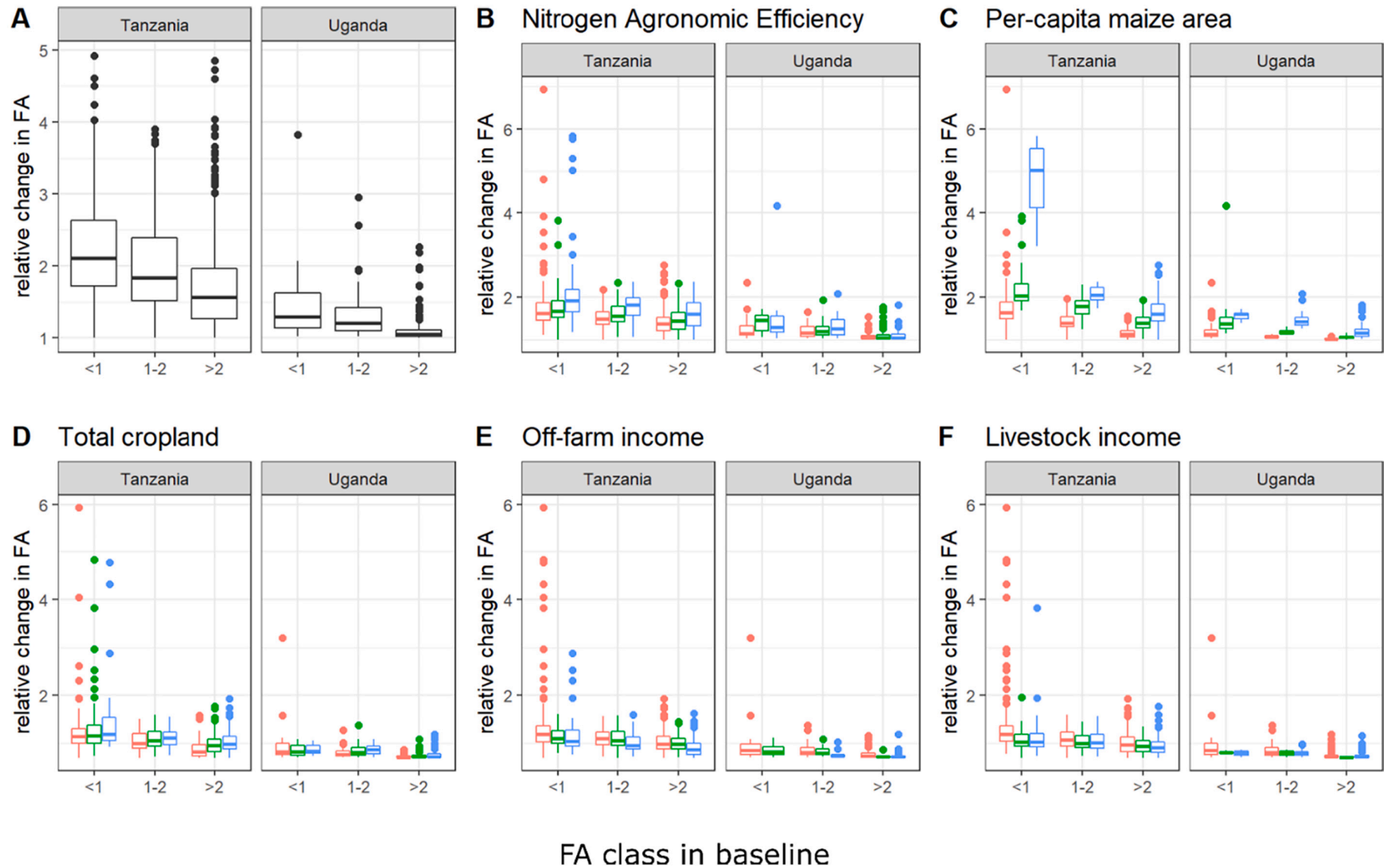


Fig. 4. Boxplots of relative change in Food availability ratio (FA) per FA class in baseline (i.e. with current reported N input on maize) in Tanzania and Uganda (A), and for three classes of nitrogen agronomic efficiency (N-AE) (B), per-capita maize area (C), total cropland (D), off-farm income (E) and livestock income (F). Red boxplot are households below the 33th percentile of the considered N-AE or farm characteristic, green boxplots are households between the 33th and 66th percentile, and blue boxplots are households above the 66th percentile. The y-axis was log-transformed so that $y = \log(\text{relative change in FA} + 1)$. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

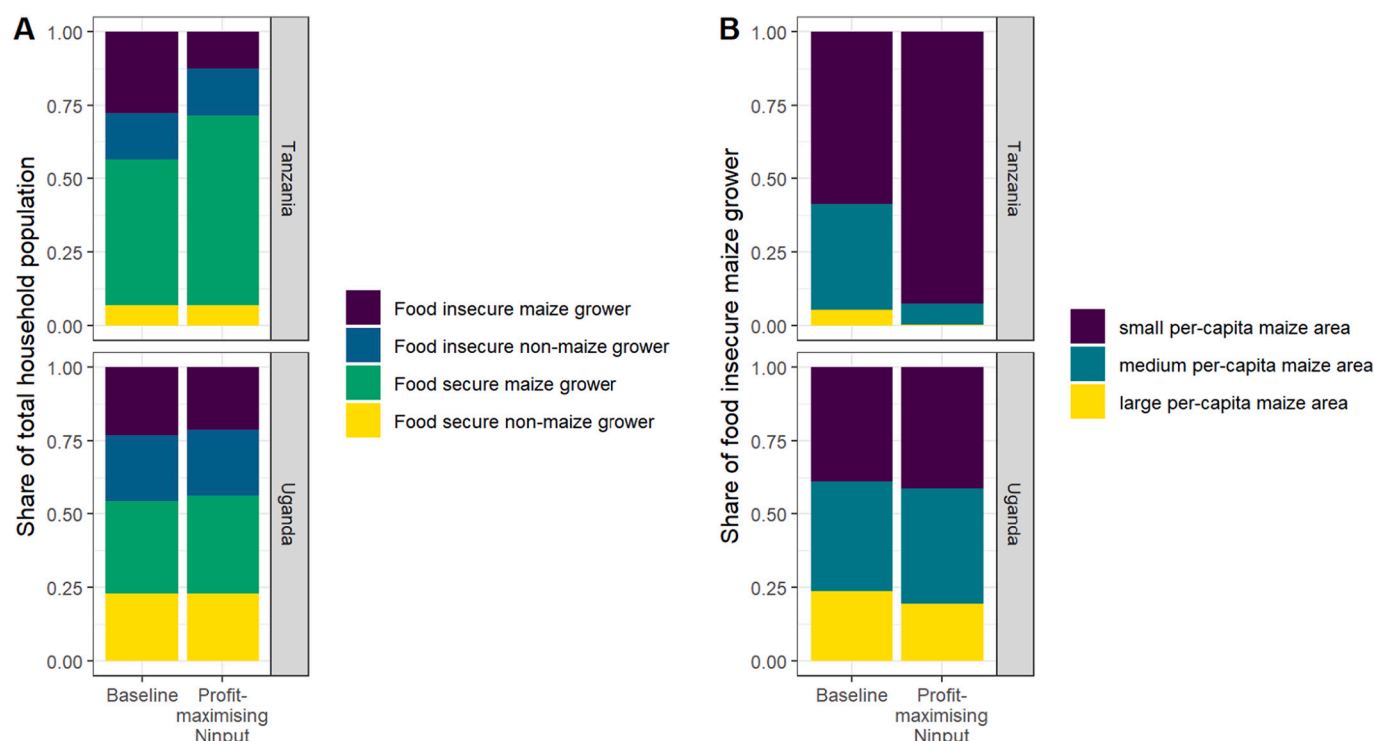


Fig. 5. (A) Share of food insecure maize growers in total agricultural household population in baseline situation (current maize yield) and with profit-maximizing N input on maize in Uganda and Tanzania and (B) share of these food insecure maize growers who have small per-capita maize area (<0.17 ha in Tanzania and <0.03 in Uganda), medium per-capita maize area ($0.17\text{--}0.38$ ha in Tanzania and $0.03\text{--}0.07$ in Uganda) and large per-capita maize area (>0.38 in Tanzania and >0.07 in Uganda).

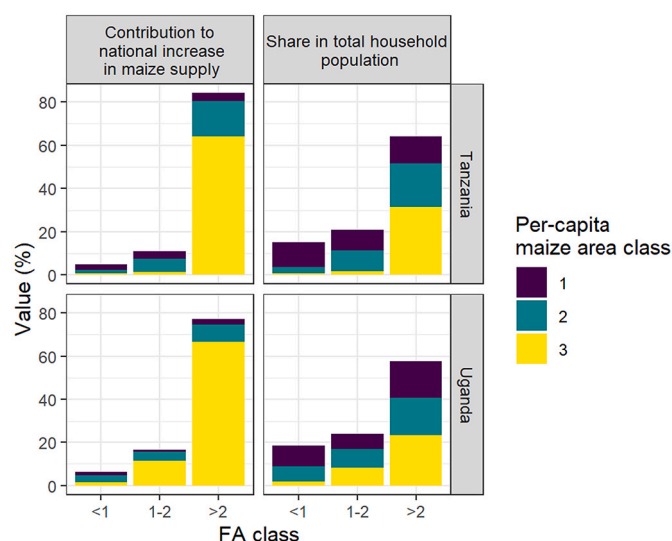


Fig. 6. Comparison between the i) relative contribution to national increase in maize supply and ii) share in total household population, for household of contrasting food availability ratio (FA) and maize area per capita classes in Tanzania and Uganda. Class 1 for per-capita maize area is <0.17 ha in Tanzania and <0.03 in Uganda, class 2 for per-capita maize area is $0.17\text{--}0.38$ ha in Tanzania and $0.03\text{--}0.07$ in Uganda, and class 3 for per-capita maize area is >0.38 in Tanzania and >0.07 in Uganda.

growers for whom fertilizer is currently not profitable. Input subsidy programs through which farmers can access fertilizer at below-market prices have been on the rise again since 2010 in several countries of SSA (Jayne et al., 2018b). Despite failing to target the poorer farmers in a number of instances (Pan and Christiaensen, 2012; Jayne et al., 2013), these programs have had a measurable impact on maize productivity. For example, the Farm Input Subsidy Program (FISP) in Malawi brought a 17% increase in farmers' gross margin (Karamba and Winters, 2015). Reducing transport costs (with e.g. improvements in road conditions) could also contribute to lower fertilizer cost and improve the profitability of fertilizer use (Guo et al., 2009). For example, the average N fertilizer price of 0.39 USD kg^{-1} in Illinois (USA) during 2001–2013 (Beckman and Riche, 2015) is about 17% of the estimated price across Tanzania and Uganda in this study (2.34 USD kg^{-1}). The much lower N cost reported by Beckman and Riche (2015) corresponds to the lower limit of N cost explored in the sensitivity analysis of this study; this boundary is therefore not unrealistic for prices elsewhere in the world. On the other hand, with a 75% increase in N fertilizer price, profit-maximizing N input in Tanzania was predicted to drop to zero, highlighting the drastic impact that the current rise in fossil fuel prices, and thus N fertilizer prices, is likely to have on food security in SSA. Seasonal variations in maize grain prices (Bonilla Cedrez et al., 2020b) can also impact fertilizer profitability. Poor households usually sell their production soon after harvest when prices are usually low, because they have no storage facilities and/or need cash. In our study, we considered annualized maize grain prices, while farmers who are equipped with adequate storage facilities and well connected to markets, may want to sell their extra produce during the lean season when maize prices are higher (Burke et al., 2020).

Profit-maximizing N input rates increase with improved N use efficiency by maize (higher N-AE values), which can enlarge the share of beneficiaries from intensification of maize production, especially in Uganda. The average predicted N-AE for maize in our study was 20 kg

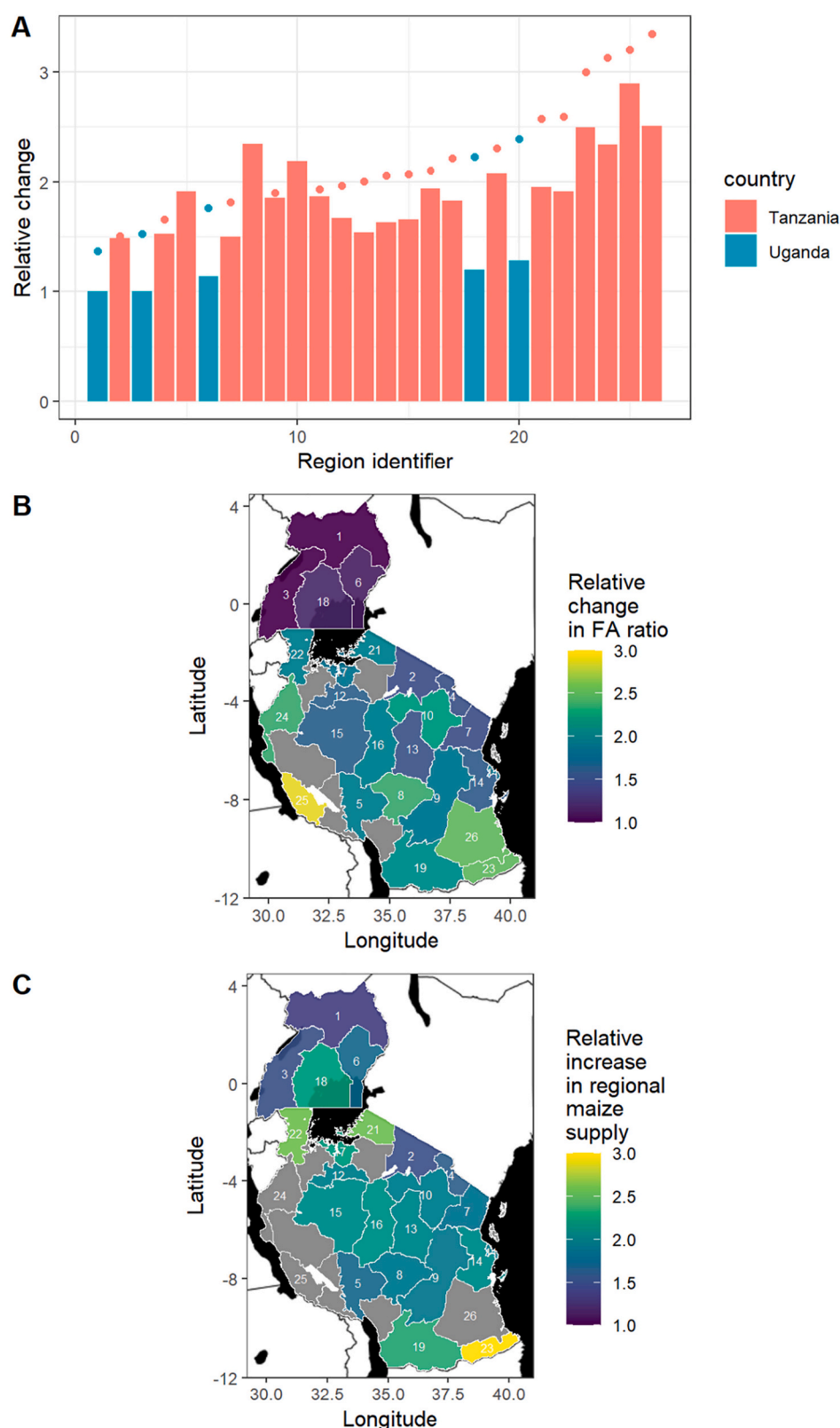


Fig. 7. A) Relative change in regional maize supply (dots) and median relative change in household-level food availability (FA) ratio for food insecure maize-growers (with the use of additional, profit-maximizing N input), in regions of Uganda and Tanzania (bars), B) map of regional median relative change in food availability ratio for food insecure maize-growers, and C) map of relative increase in regional maize supply. Numbers in the map are number of regions that correspond with the Region identifier along the x-axis of fig. A.

grain yield kg^{-1} N added (for a N input of 40 kg N ha^{-1}), which is well below the 32 kg kg N^{-1} or more that can be achieved in well-managed maize fields (ten Berge et al., 2019; Vanlauwe et al., 2011). Our model was trained with mostly on-farm data, with possibly sub-optimal weed, pest and disease management affecting N-AE. More generally, improving the synchrony between crop demand and N supply following

the “4R” nutrient management framework (“using the right N source at the right rate, right time and in the right place”, Udvardi et al., 2021) is also key to achieve greater N-AE.

Our analysis showed that for most farm households in Tanzania, the use of additional N fertilizer was profitable. Yet, the question remains why these farmers do not actually use (more) fertilizer. One reason could

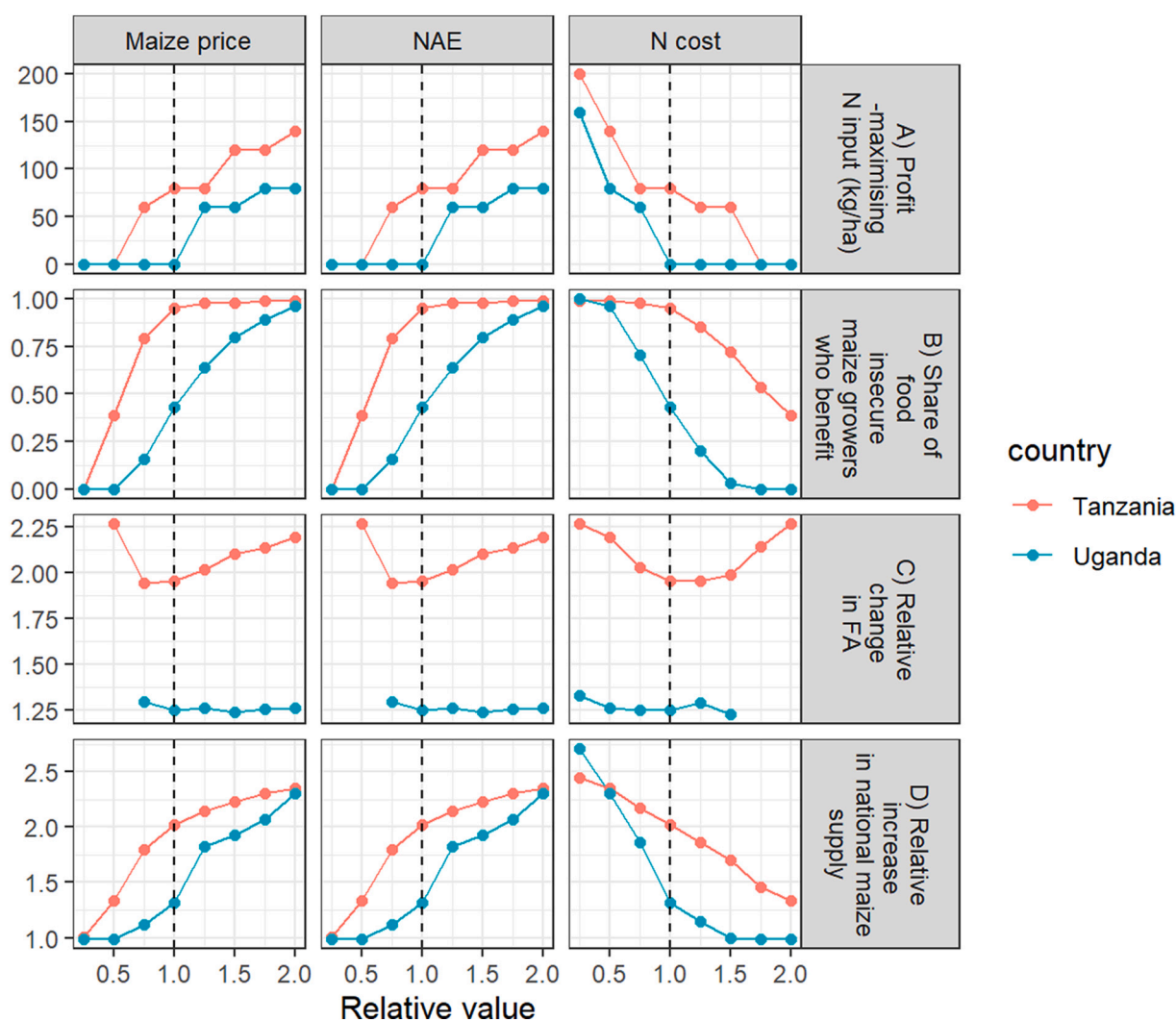


Fig. 8. Sensitivity analysis of the impact of a change in maize price, nitrogen agronomic efficiency (N-AE) and N cost on A) profit-maximizing N input, B) share of food insecure maize growers who increase their food availability ratio with the use of additional profit-maximizing N input on maize, C) median relative change in food availability ratio (FA) for food insecure maize growers, and D) relative increase in national maize supply due to the use of additional N input on maize, in Tanzania and Uganda.

be that farmers lack capital to buy fertilizer, possibly also because credit options to finance its purchase at the start of the season are scarce or do not exist. Another explanation could be the usual risk averse nature of farmers, associated with e.g. exposure to drought (Assefa et al., 2021; Jourdain et al., 2020). While fertilizer use might be profitable on average, in years with, for example, drought stress leading to poor yields, farmers would not break even (e.g. Bielders and Gérard, 2015). In addition, in our study we assumed that farmers would apply the profit-maximizing N fertilizer input. However, in reality farmers might only go for more N fertilizer if the increment in gross margin exceeds the extra N cost by a safety margin. A value:cost ratio of two is typically used as a basis for adoption of a technology (e.g. Jayne et al., 2018b). Lastly, the extra cost of labour for fertilizer application was not considered in our study; including it would also lower the estimated profitability of fertilizer use.

4.2. National food security vs household-level food security

The use of additional N fertilizer was predicted to substantially increase overall regional and national maize production. The food riots of 2008, the COVID-19 outbreak, and the recent war in Ukraine have emphasized the vulnerability of relying heavily on food imports to

national governments and revived the idea of national and regional food self-sufficiency (d'Amour et al., 2016; Fontan Sers and Mughal, 2020). Building resilience in SSA's states to the consequences of such events, while meeting a growing food demand with population growth and avoiding further cropland expansion, requires drastic increases in cereal yields. Van Ittersum et al. (2016) calculated that cereal yields have to increase to close to 80% of their water-limited yield potential to feed the population in SSA by 2050, and this will require a 15-fold increase in nutrient inputs (ten Berge et al., 2019). Our study helps identify regions where the scope to increase maize production is greatest (see Fig. 7C). However, these priority regions in terms of national food security do not necessarily match with the regions where the scope to improve household-level food security is the strongest (see Fig. 7B). Policy interventions that prioritize national food security will require specific attention to this, ensuring that “no one is left behind” (United Nations, 2015).

4.3. Long-term sustainability of cropping systems

Although relatively small profit-maximizing N fertilizer inputs (80 kg N ha⁻¹ in Tanzania, and 20 kg N ha⁻¹ in Uganda) may yield immediate benefits for household food security, these inputs are unlikely to be

sufficient to avoid soil mining and to guarantee long-term sustainability of maize-based systems. Ten Berge et al. (2019) calculated that on average a minimum of 140–150 kg N ha⁻¹ must be available to maize crop to sustain yields compatible with SSA food self-sufficiency by 2050, i.e. far more than the profit-maximizing N fertilizer inputs computed in our study. Recycling of biomass, use of farmyard manure, rotating with grain legumes and use of leguminous trees in agroforestry systems can complement mineral fertilizer to provide the N required to sustain high maize yields in future. The increased N fertilizer input required to achieve household and national food security, while preserving long-term soil fertility, comes, however, at a cost for the environment in the form of N leaching losses and gaseous emissions. Narrowing the maize yield gap in SSA will undoubtedly increase N₂O emissions (Leitner et al., 2020). Yet, ten Berge et al. (2019) estimated that meeting the food demand in SSA by 2050 through intensification of cereal production with mineral fertilizer, assuming good agronomy and using the ‘4R’ principles of nutrient management, would emit less greenhouse gases than through cropland expansion from deforestation. Large fertilizer inputs, if not retained in soils, can also contribute to eutrophication in lakes, inland and coastal waters, with direct threats to biodiversity and human health. The ‘4R’ approach to nutrient management that is crucial for increasing nutrient use efficiency and profitability, will at the same time reduce leaching and run-off of nutrients causing eutrophication.

4.4. Opportunities to use and improve the proposed framework

Extending our analysis to other countries or regions with larger land holdings and possibly larger maize area per capita would be necessary to fully grasp the potential of maize intensification to contribute to improved food security throughout SSA, e.g. in the cotton basin in Mali the median cultivated land area per capita is 0.84 ha compared with 0.13 ha in central Malawi and 0.14 ha in the Ethiopian highlands (Giller et al., 2021). Besides, other crops than maize, e.g. traditional grains like sorghum and millet, rice, legumes (e.g. groundnut and cowpea), highland banana, root and tuber crops and vegetables, have to be considered to quantify the full potential of intensification and diversification of crop production to reduce food insecurity. It will however, be challenging to do this with an empirical model as there is less data available for these types of crops than for maize.

The accuracy of the RF model of our study ($R^2 = 0.82$) was better than that of a model trained on yields measured in 601 field trials in Tanzania ($R^2 = 0.24$, Palmas and Chamberlin, 2020), highlighting the importance of training the model on a large dataset. The main features of our model were in line with the findings of a meta-analysis of 71 studies across SSA that showed that soil texture, pH and exchangeable K were the main factors explaining variability in N-AE (Ichami et al., 2019). Soils can vary substantially in macro and micro-nutrient content at short distances – owing to past crop management by farmers (Falconnier et al., 2016). The variations of crop responses to nutrient inputs depending on rainfall season (short vs long in area with two growing seasons per year) would also deserve further analysis. With the current data, total rainfall, and other indicators related to its distribution, only marginally improved the ability of the RF model to explain maize yield variability. Process-based crop models could be used to simulate crop responses to fertilizer inputs. This type of models can be calibrated with data from a limited set of trials spread across representative locations and then used to make predictions at any location (see Deng et al., 2019 for an example). More specifically, process-based crop models can account for the impact of drought or excessive rainfall on fertilizer use efficiency, and are useful to determine the probability of yield failure and the risk of not breaking-even when using fertilizer (e.g. Ricome et al., 2017). Risk assessment will help to further distinguish areas where fertilizer use is a low-risk opportunity for farmers and those where its use is too risky and must be complemented with specific interventions [e.g. index-based insurance (Benami et al., 2021)].

Lastly, local variations in prices of maize and costs of fertilizer, due to e.g. transportation costs that are not included in the spatial price predictions, and uncertainty of farmer-reported crop areas are substantial sources of uncertainty in our analysis, as pointed out in our sensitivity analysis. Our study and the proposed framework could therefore guide national and regional priority settings of interventions around intensification of maize production with fertilizer, but should be complemented with place-based assessments of the local relevance of proposed interventions.

5. Conclusions

Intensification of maize production with mineral fertilizer can substantially improve the food security of food insecure households in Uganda and Tanzania. Households with relatively large per-capita maize area benefit most, as well as those located in areas where maize yields are low in the absence of fertilizer use and where yield responses to nutrients are high. In some areas, particularly in Uganda, profit-maximizing N fertilizer input is low, and the potential of maize intensification through fertilizers to reduce food insecurity is thus limited. Institutional commitment to smart input subsidies and investments in road networks could lower fertilizer price, and broader investments in agricultural research, development and extension to operationalize best-practices (better seed quality, timely planting, optimal plant density, and proper weed, pest and disease management) could help to improve nutrient use efficiency by crops. Our study brings important insights for priority setting as high potential areas for increased maize domestic production do not necessarily match with areas where there is immediate scope for improving household-level food security. These two impact levels should be coherently considered when articulating policy and research priorities that aim at improving food security at household level and regionally.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

Acknowledgements

The lead author is grateful to the CIRAD-Persyst department that provided funds for the workshop that allowed to initiate this study. M.K. v.I and K.E.G. acknowledge grants from the NWO-WOTRO Strategic Partnership NL-CGIAR.

Supplementary data

Supplementary data to this article can be found online at <https://doi.org/10.1016/j.agsy.2022.103588>.

References

- Affholder, F., 1997. Empirically modelling the interaction between intensification and climatic risk in semiarid regions. *Field Crop Res.* 52, 79–93. [https://doi.org/10.1016/S0378-4290\(96\)03453-3](https://doi.org/10.1016/S0378-4290(96)03453-3).
- Assefa, B.T., Reidsma, P., Chamberlin, J., van Ittersum, M.K., 2021. Farm- and community-level factors underlying the profitability of fertiliser usage for Ethiopian smallholder farmers. *Agricon* 60, 460–479. <https://doi.org/10.1080/03031853.2021.1984958>.
- Beal, T., Massiot, E., Arsenault, J.E., Smith, M.R., Hijmans, R.J., 2017. Global trends in dietary micronutrient supplies and estimated prevalence of inadequate intakes. *PLoS One* 12, e0175554. <https://doi.org/10.1371/journal.pone.0175554>.

- Beckman, J., Riche, S., 2015. Changes to the natural gas, CORN, and fertilizer price relationships from the biofuels era. *J. Agric. Appl. Econ.* 47, 494–509. <https://doi.org/10.1017/aae.2015.22>.
- Benami, E., Jin, Z., Carter, M.R., Ghosh, A., Hijmans, R.J., Hobbs, A., Kenduiwo, B., Lobell, D.B., 2021. Uniting remote sensing, crop modelling and economics for agricultural risk management. *Nat Rev Earth Environ* 2, 140–159. <https://doi.org/10.1038/s43017-020-00122-y>.
- Bielders, C.L., Gérard, B., 2015. Millet response to microdose fertilization in South-Western Niger: effect of antecedent fertility management and environmental factors. *Field Crop Res.* 171, 165–175. <https://doi.org/10.1016/j.fcr.2014.10.008>.
- Bonilla Cedrez, C., Chamberlin, J., Guo, Z., Hijmans, R.J., 2020a. Spatial variation in fertilizer prices in sub-Saharan Africa. *PLoS One* 15, e0227764. <https://doi.org/10.1371/journal.pone.0227764>.
- Bonilla Cedrez, C., Chamberlin, J., Hijmans, R.J., 2020b. Seasonal, annual, and spatial variation in cereal prices in Sub-Saharan Africa. *Glob Food Sec* 26, 100438. <https://doi.org/10.1016/j.gfs.2020.100438>.
- Bonilla Cedrez, C., Chamberlin, J., Hijmans, R.J., 2021. Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nat Food* 2, 766–772. <https://doi.org/10.1038/s43016-021-00370-1>.
- Breiman, L., 2001. Random forests. *Mach. Learn.* 45, 5–32. <https://doi.org/10.1023/A:1010933404324>.
- Burke, W.J., Snapp, S.S., Jayne, T.S., 2020. An in-depth examination of maize yield response to fertilizer in Central Malawi reveals low profits and too many weeds. *Agric. Econ.* 51, 923–940. <https://doi.org/10.1111/agec.12601>.
- Coates, J., Swindale, A., Bilinsky, P., 2007. Household Food Insecurity Access Scale (HFAS) for Measurement of Food Access: Indicator Guide: Version 3, 576842013-001. <https://doi.org/10.1037/e576842013-001>.
- Cobo, J.G., Dercon, G., Cadisch, G., 2010. Nutrient balances in African land use systems across different spatial scales: a review of approaches, challenges and progress. *Agric. Ecosyst. Environ.* 136, 1–15. <https://doi.org/10.1016/j.agee.2009.11.006>.
- d'Amour, C.B., Wenz, L., Kalkuhl, M., Steckel, J.C., Creutzig, F., 2016. Teleconnected food supply shocks. *Environ. Res. Lett.* 11, 035007. <https://doi.org/10.1088/1748-9326/11/3/035007>.
- Demont, M., Jouve, P., Stessens, J., Tollens, E., 2007. Boserup versus Malthus revisited: evolution of farming systems in northern Côte d'Ivoire. *Agric. Syst.* 93, 215–228. <https://doi.org/10.1016/j.agry.2006.05.006>.
- Dillon, B., Barrett, C.B., 2017. Agricultural factor markets in sub-Saharan Africa: an updated view with formal tests for market failure. In: *Food Policy, Agriculture in Africa – Telling Myths from Facts*, 67, pp. 64–77. <https://doi.org/10.1016/j.foodpol.2016.09.015>.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. *Field Crop Res.* 187, 113–126. <https://doi.org/10.1016/j.fcr.2015.12.015>.
- FAO, 2001. Human energy requirements. In: *Food and Nutrition Technical Report. Food and Agriculture Organization of the United Nations*, Rome, p. 103.
- FAO, IFAD, UNICEF, WFP, WHO, 2022. The State of Food Security and Nutrition in the World 2022: Repurposing Food and Agricultural Policies to Make Healthy Diets more Affordable, the State of Food Security and Nutrition in the World (SOFI). FAO, IFAD, UNICEF, WFP, WHO, Rome, Italy. <https://doi.org/10.4060/cc0639en>.
- FAOSTAT, 2018. Food and Agriculture Organization of the United Nations Rome, Italy. <http://faostat.fao.org>.
- Fontan Sers, C., Mughal, M., 2020. Covid-19 outbreak and the need for rice self-sufficiency in West Africa. *World Dev.* 135, 105071. <https://doi.org/10.1016/j.worlddev.2020.105071>.
- Franke, A.C., van den Brand, G.J., Vanlauwe, B., Giller, K.E., 2018. Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agric. Ecosyst. Environ.* 261, 172–185. <https://doi.org/10.1016/j.agee.2017.09.029>.
- Fraval, S., Hammond, J., Wichern, J., Oosting, S.J., Boer, I.J.M.D., Teufel, N., Lannerstad, M., Waha, K., Pagella, T., Rosenstock, T.S., Giller, K.E., Herrero, M., Harris, D., Wijk, M.T.V., 2019. Making the most of imperfect data: a critical evaluation of standard information collected in farm household surveys. *Exp. Agric.* 55, 230–250. <https://doi.org/10.1017/S0014479718000388>.
- Frelat, R., Lopez-Ridaura, S., Giller, K.E., Herrero, M., Douchamps, S., Djurfeldt, A.A., Erenstein, O., Henderson, B., Kassie, M., Paul, B.K., Rigolot, C., Ritzema, R.S., Rodriguez, D., van Asten, P.J.A., van Wijk, M.T., 2016. Drivers of household food availability in sub-Saharan Africa based on big data from small farms. *Proc. Natl. Acad. Sci. U. S. A.* 113, 458–463. <https://doi.org/10.1073/pnas.1518384112>.
- Giller, K.E., Delaune, T., Silva, J.V., van Wijk, M., Hammond, J., Descheemaeker, K., van de Ven, G., Schut, A.G.T., Tauliya, G., Chikowo, R., Andersson, J.A., 2021. Small farms and development in sub-Saharan Africa: farming for food, for income or for lack of better options? *Food Sec.* <https://doi.org/10.1007/s12571-021-01209-0>.
- Greenwell, B., 2017. Pdp: an R package for constructing partial dependence plots. *The R J.* 421–436.
- Greenwell, B., Boehmke, B., Gray, B., 2020. vip: Variable Importance Plots.
- Guo, Z., Koo, J., Wood, S., 2009. Fertilizer profitability in East Africa: a spatially explicit policy analysis (No. 51710). In: 2009 Conference, August 16–22, 2009, Beijing, China, 2009 Conference, August 16–22, 2009, Beijing, China. International Association of Agricultural Economists.
- Haggblade, S., Hazell, P., Reardon, T., 2010. The rural non-farm economy: prospects for growth and poverty reduction. In: *World Development, The Future of Small Farms*, 38, pp. 1429–1441. <https://doi.org/10.1016/j.worlddev.2009.06.008>.
- Hammond, J., Fraval, S., van Eten, J., Suchini, J.G., Mercado, L., Pagella, T., Frelat, R., Lannerstad, M., Douchamps, S., Teufel, N., Valbuena, D., van Wijk, M.T., 2017. The rural household multi-indicator survey (RHOMIS) for rapid characterisation of households to inform climate smart agriculture interventions: description and applications in East Africa and Central America. *Agric. Syst.* 151, 225–233. <https://doi.org/10.1016/j.agry.2016.05.003>.
- Hartkamp, A.D., White, J.W., Rodriguez Aguilera, A., Bänziger, M., Srinivasan, G., Granados, G., 2000. *Maize Production Environments Revisited*. CIMMYT Mexico.
- Hengl, T., Heuvelink, G.B.M., Kempen, B., Leenaars, J.G.B., Walsh, M.G., Shepherd, K.D., Sila, A., MacMillan, R.A., Jesus, J.M., Tamene, L., Tondoh, J.E., 2015. Mapping Soil Properties of Africa at 250 m Resolution: Random Forests Significantly Improve Current Predictions. *PLOS ONE* 10, e0125814. <https://doi.org/10.1371/journal.pone.0125814>.
- Hengl, T., Leenaars, J.G.B., Shepherd, K.D., Walsh, M.G., Heuvelink, G.B.M., Mamo, T., Tilahun, H., Berkhout, E., Cooper, M., Fegraus, E., Wheeler, I., Kwabena, N.A., 2017. Soil nutrient maps of Sub-Saharan Africa: assessment of soil nutrient content at 250 m spatial resolution using machine learning. *Nutr. Cycl. Agroecosyst.* 109, 77–102. <https://doi.org/10.1007/s10705-017-9870-x>.
- Ichami, S.M., Shepherd, K.D., Sila, A.M., Stoorvogel, J.J., Hoffland, E., 2019. Fertilizer response and nitrogen use efficiency in African smallholder maize farms. *Nutr. Cycl. Agroecosyst.* 113, 1–19. <https://doi.org/10.1007/s10705-018-9958-y>.
- Jayne, T.S., Mason, N.M., Burke, W.J., Ariga, J., 2018. Review: Taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy* 75, 1–14. <https://doi.org/10.1016/j.foodpol.2018.01.003>.
- Jayne, T., Mather, D., Mason, N., Ricker-Gilbert, J., 2013. How do fertilizer subsidy programs affect total fertilizer use in sub-Saharan Africa? Crowding out, diversion, and benefit/cost assessments. *Agric. Econ.* 44, 687–703. <https://doi.org/10.1111/agec.12082>.
- IPFRI, 2020. Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017. Harvard, Dataserve, p. V3.
- Jayne, T.S., Chamberlin, J., Benfica, R., 2018a. Africa's unfolding economic transformation. *J. Dev. Stud.* 54, 777–787. <https://doi.org/10.1080/00220388.2018.1430774>.
- Jayne, T.S., Mason, N.M., Burke, W.J., Ariga, J., 2018b. Review: taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy* 75, 1–14. <https://doi.org/10.1016/j.foodpol.2018.01.003>.
- Jourdain, D., Lairez, J., Striffler, B., Affholder, F., 2020. Farmers' preference for cropping systems and the development of sustainable intensification: a choice experiment approach. *Rev Agric Food Environ Stud* 101, 417–437. <https://doi.org/10.1007/s41130-020-00100-4>.
- Karamba, R.W., Winters, P.C., 2015. Gender and agricultural productivity: implications of the farm input subsidy program in Malawi. *Agric. Econ.* 46, 357–374. <https://doi.org/10.1111/agec.12169>.
- Kihara, J., Nziguheba, G., Zingore, S., Coulbaly, A., Esilaba, A., Kabambe, V., Njoroge, S., Palm, C., Huising, J., 2016. Understanding variability in crop response to fertilizer and amendments in sub-Saharan Africa. *Agric. Ecosyst. Environ.* 229, 1–12. <https://doi.org/10.1016/j.agee.2016.05.012>.
- Kihara, J., Sileshi, G.W., Nziguheba, G., Kinyua, M., Zingore, S., Sommer, R., 2017. Application of secondary nutrients and micronutrients increases crop yields in sub-Saharan Africa. *Agron. Sustain. Dev.* 37, 25. <https://doi.org/10.1007/s13593-017-0431-0>.
- Kilic, T., Winters, P., Carletto, C., 2015. Gender and agriculture in sub-Saharan Africa: introduction to the special issue. *Agric. Econ.* 46, 281–284. <https://doi.org/10.1111/agec.12165>.
- Kuyah, S., Whitney, C.W., Jonsson, M., Sileshi, G.W., Öborn, I., Muthuri, C.W., Luedeling, E., 2019. Agroforestry delivers a win-win solution for ecosystem services in sub-Saharan Africa. A meta-analysis. *Agron. Sustain. Dev.* 39, 47. <https://doi.org/10.1007/s13593-019-0589-8>.
- Leitner, S., Pelster, D.E., Werner, C., Merbold, L., Baggs, E.M., Mapanda, F., Butterbach-Bahl, K., 2020. Closing maize yield gaps in sub-Saharan Africa will boost soil N2O emissions. In: *Current Opinion in Environmental Sustainability, Climate Change, Reactive Nitrogen, Food Security and Sustainable Agriculture*, 47, pp. 95–105. <https://doi.org/10.1016/j.cosust.2020.08.018>.
- Lowder, S.K., Sánchez, M.V., Bertini, R., 2021. Which farms feed the world and has farmland become more concentrated? *World Dev.* 142, 105455. <https://doi.org/10.1016/j.worlddev.2021.105455>.
- Luan, Y., Cui, X., Ferrat, M., 2013. Historical trends of food self-sufficiency in Africa. *Food Sec.* 5, 393–405. <https://doi.org/10.1007/s12571-013-0260-1>.
- Mapanda, F., Wuta, M., Nyamangara, J., Rees, R.M., 2012. Nitrogen leaching and indirect nitrous oxide emissions from fertilized croplands in Zimbabwe. *Nutr. Cycl. Agroecosyst.* 94, 85–96. <https://doi.org/10.1007/s10705-012-9528-7>.
- Masters, W.A., Rosenblum, N.Z., Alemu, R.G., 2018. Agricultural transformation, nutrition transition and food policy in Africa: Preston curves reveal new stylised facts. *J. Dev. Stud.* 54, 788–802. <https://doi.org/10.1080/00220388.2018.1430768>.
- Mendez del Villar, P., Lançon, F., 2015. West African rice development: beyond protectionism versus liberalization? In: *Global Food Security, Special Section on Selected papers from the 3rd Africa Rice Congress*, 5, pp. 56–61. <https://doi.org/10.1016/j.gfs.2014.11.001>.
- Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. *Field Crop Res.* 214, 321–330. <https://doi.org/10.1016/j.fcr.2017.09.026>.
- Nziguheba, G., van Heerwaarden, J., Vanlauwe, B., 2021. Quantifying the prevalence of (non-)response to fertilizers in sub-Saharan Africa using on-farm trial data. *Nutr. Cycl. Agroecosyst.* 121, 257–269. <https://doi.org/10.1007/s10705-021-10174-1>.
- OCDE, FAO, 2016. *Agriculture in sub-Saharan Africa: Prospects and challenges for the next decade*. In: *OECD-FAO Agricultural Outlook 2016–2025*. Paris.
- Palmas, S., Chamberlin, J., 2020. Fertilizer profitability for smallholder maize farmers in Tanzania: a spatially-explicit ex ante analysis. *PLoS One* 15, e0239149. <https://doi.org/10.1371/journal.pone.0239149>.

- Pan, L., Christiaensen, L., 2012. Who is vouching for the input voucher? Decentralized targeting and elite capture in Tanzania. *World Dev.* 40, 1619–1633. <https://doi.org/10.1016/j.worlddev.2012.04.012>.
- Rakotoarisoa, M.A., Iafate, M., Paschali, M., 2011. Why Has Africa Become a Net Food Importer? - Explaining Africa Agricultural and Food Trade Deficits. Rural Infrastructure and Agro-Industries Division, FAO, Rome, Italy.
- Ricciardi, V., Ramankutty, N., Mehrabi, Z., Jarvis, L., Chookolingo, B., 2018. How much of the world's food do smallholders produce? *Global Food Sec.* 17, 64–72. <https://doi.org/10.1016/j.gfs.2018.05.002>.
- Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., Sall, M., 2017. Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. *Agric. Syst.* 156, 149–176. <https://doi.org/10.1016/j.agsy.2017.05.015>.
- Ritzema, R.S., Frelat, R., Douxchamps, S., Silvestri, S., Rufino, M.C., Herrero, M., Giller, K.E., López-Ridaura, S., Teufel, N., Paul, B.K., van Wijk, M.T., 2017. Is production intensification likely to make farm households food-adequate? A simple food availability analysis across smallholder farming systems from east and West Africa. *Food Sec.* 9, 115–131. <https://doi.org/10.1007/s12571-016-0638-y>.
- Ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., de Groot, H.L.E., van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Sec.* 23, 9–21. <https://doi.org/10.1016/j.gfs.2019.02.001>.
- Tittonell, P., Muriuki, A., Shepherd, K.D., Mugendi, D., Kaizzi, K.C., Okeyo, J., Verchot, L., Coe, R., Vanlauwe, B., 2010. The diversity of rural livelihoods and their influence on soil fertility in agricultural systems of East Africa – a typology of smallholder farms. *Agric. Syst.* 103, 83–97. <https://doi.org/10.1016/j.agsy.2009.10.001>.
- Udvardi, M., Below, F.E., Castellano, M.J., Eagle, A.J., Giller, K.E., Ladha, J.K., Liu, X., Maaz, T.M., Nova-Franco, B., Raghuram, N., Robertson, G.P., Roy, S., Saha, M., Schmidt, S., Tegeder, M., York, L.M., Peters, J.W., 2021. A research road map for responsible use of agricultural nitrogen. *Front. Sustain. Food Syst.* 5.
- United Nations, 2015. Transforming our world: the 2030 Agenda for Sustainable Development. Department of Economic and Social Affairs [WWW Document]. URL: <https://sdgs.un.org/2030agenda> (accessed 7.1.22).
- van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? *Proc. Natl. Acad. Sci. U. S. A.* 113, 14964–14969. <https://doi.org/10.1073/pnas.1610359113>.
- van Loon, M.P., Hijbeek, R., Ten Berge, H.F.M., Sy, V.D., Ten Broeke, G.A., Solomon, D., van Ittersum, M.K., 2019. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Glob. Chang. Biol.* 25, 3720–3730. <https://doi.org/10.1111/gcb.14783>.
- van Wijk, M., Hammond, J., Gorman, L., Adams, S., Ayantunde, A., Baines, D., Bolliger, A., Bosire, C., Carpena, P., Chesterman, S., Chinyophiro, A., Daudi, H., Dongsop, P., Douxchamps, S., Emera, W.D., Fraval, S., Fonte, S., Hok, L., Kiara, H., Kihoro, E., Korir, L., Lamanna, C., Long, C.T.M., Manyawu, G., Mehrabi, Z., Mengistu, D.K., Mercado, L., Meza, K., Mora, V., Mutemi, J., Ng'endo, M., Njingulula, P., Okafor, C., Pagella, T., Phengsavanh, P., Rao, J., Ritzema, R., Rosenstock, T.S., Skirrow, T., Steinke, J., Stirling, C., Gabriel Suchini, J., Teufel, N., Thorne, P., Vanek, S., van Etten, J., Vanlauwe, B., Wichern, J., Yameogo, V., 2020. The Rural Household Multiple Indicator Survey, data from 13,310 farm households in 21 countries. *Sci Data* 7, 46. <https://doi.org/10.1038/s41597-020-0388-8>.
- Vanlauwe, B., Bationo, A., Chianu, J., Giller, K.E., Merckx, R., Mokwunye, U., Ohiokepehai, O., Pypers, P., Tabo, R., Shepherd, K.D., Smaling, E.M.A., Woomer, P.L., Sanginga, N., 2010. Integrated soil fertility management, operational definition and consequences for implementation and dissemination. *Outlook Agric.* 39, 8.
- Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P., 2014. Sustainable intensification and the African smallholder farmer. *Current Opinion in Environmental Sustainability* 8, 15–22. <https://doi.org/10.1016/j.cosust.2014.06.001>.
- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339, 35–50. <https://doi.org/10.1007/s11104-010-0462-7>.
- Wichern, J., van Wijk, M.T., Descheemaeker, K., Frelat, R., van Asten, P.J.A., Giller, K.E., 2017. Food availability and livelihood strategies among rural households across Uganda. *Food Sec.* 9, 1385–1403. <https://doi.org/10.1007/s12571-017-0732-9>.
- Wichern, J., van Heerwaarden, J., de Bruin, S., Descheemaeker, K., van Asten, P.J.A., Giller, K.E., van Wijk, M.T., 2018. Using household survey data to identify large-scale food security patterns across Uganda. *PLoS One* 13, e0208714. <https://doi.org/10.1371/journal.pone.0208714>.
- Wichern, J., Descheemaeker, K., Giller, K.E., Ebanyat, P., Taulya, G., van Wijk, M.T., 2019. Vulnerability and adaptation options to climate change for rural livelihoods – a country-wide analysis for Uganda. *Agric. Syst.* 176, 102663. <https://doi.org/10.1016/j.agsy.2019.102663>.
- World Bank, 2021a. Arable land (hectares per person) - Sub-Saharan Africa. <https://data.worldbank.org/indicator/AG.LND.ARBL.HA.PC?locations=ZG> last accessed 09/12/2021.
- World Bank, 2021b. Living Standards Measurement Study - LSMS-ISA. Uganda. <https://www.worldbank.org/en/programs/lsms/initiatives/lsms-isa#43> last accessed 07/12/2021.
- World Bank, 2021c. Living Standards Measurement Study - LSMS-ISA. Tanzania. <https://www.worldbank.org/en/programs/lsms/initiatives/lsms-isa#7> last accessed 07/12/2021.

The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in sub-Saharan Africa

Outlook on Agriculture
2023, Vol. 52(3) 311–326
© The Author(s) 2023



Article reuse guidelines:
sagepub.com/journals-permissions
DOI: 10.1177/00307270231199795
journals.sagepub.com/home/oag



Gatien N Falconnier^{1,2,3,4} , Rémi Cardinael^{1,2,4},
Marc Corbeels^{1,5,6}, Frédéric Baudron³, Pauline Chivenge⁷,
Antoine Couëdel^{1,8}, Aude Ripoché^{1,9,10,11} ,
François Affholder^{1,12}, Krishna Naudin^{1,8}, Emilie Benailon^{1,8},
Leonard Rusinamhodzi¹³, Louise Leroux^{1,5,6},
Bernard Vanlauwe⁶ and Ken E Giller¹⁴

Abstract

Can farmers in sub-Saharan Africa (SSA) boost crop yields and improve food availability *without* using more mineral fertilizer? This question has been at the center of lively debates among the civil society, policy-makers, and in academic editorials. Proponents of the “yes” answer have put forward the “input reduction” principle of agroecology, i.e. by relying on agrobiodiversity, recycling and better efficiency, agroecological practices such as the use of legumes and manure can increase crop productivity without the need for more mineral fertilizer. We reviewed decades of scientific literature on nutrient balances in SSA, biological nitrogen fixation of tropical legumes, manure production and use in smallholder farming systems, and the environmental impact of mineral fertilizer. Our analyses show that *more* mineral fertilizer is needed in SSA for five reasons: (i) the starting point in SSA is that agricultural production is “agroecological” by default, that is, very low mineral fertilizer use, widespread mixed crop-livestock systems and large crop diversity including legumes, but leading to poor soil fertility as a result of widespread soil nutrient mining, (ii) the nitrogen needs of crops cannot be adequately met solely through biological nitrogen fixation by legumes and recycling of animal manure, (iii) other nutrients like phosphorus and potassium need to be replaced continuously, (iv) mineral fertilizers, if used appropriately, cause little harm to the environment, and (v) reducing the use of mineral fertilizers would hamper productivity gains and contribute indirectly to agricultural expansion and to deforestation. Yet, the agroecological principles directly related to soil fertility—recycling, efficiency, diversity—remain key in improving soil health and nutrient-use efficiency, and are critical to sustaining crop productivity in the long run. We argue for a nuanced position that acknowledges the critical need for more mineral fertilizers in SSA, in combination with the use of agroecological practices and adequate policy support.

¹ AIDA, Univ Montpellier, CIRAD, Montpellier, France

² CIRAD, UPR AIDA, Harare, Zimbabwe

³ International Maize and Wheat Improvement Centre (CIMMYT)-Zimbabwe, Harare, Zimbabwe

⁴ Department of Plant Production Sciences and Technologies, University of Zimbabwe, Harare, Zimbabwe

⁵ CIRAD, UPR AIDA, Nairobi, Kenya

⁶ International Institute of Tropical Agriculture, Nairobi, Kenya

⁷ African Plant Nutrition Institute, UM6P Experimental Farm, Benguerir, Morocco

⁸ CIRAD, UPR AIDA, Montpellier, France

⁹ CIRAD, UPR AIDA, Saint-Denis, La Réunion, France

¹⁰ GECO, Université Montpellier, CIRAD, Montpellier, France

¹¹ CIRAD, UPR GECO, Réunion, France

¹² Universidade Eduardo Mondlane, Faculdade de Agronomia e Engenharia Florestal, Maputo, Mozambique

¹³ International Institute of Tropical Agriculture (IITA), Accra, Ghana

¹⁴ Plant Production Systems Group, Wageningen University, Wageningen, Netherlands

Corresponding author:

Gatien N Falconnier, UPR AIDA - Département Persyst Avenue Agropolis TA-BI 15/ 0234398 MONTPELLIER Cedex 5 Bâtiment 2 bureau 127, CIRAD, Montpellier, France.

Email: gatien.falconnier@cirad.fr

Keywords

nutrient balance, legumes, biological nitrogen fixation, manure, soil fertility

Introduction

Agriculture is at the cross-road of sustainability issues related to food security, biodiversity loss, environmental degradation and climate change. Alternative approaches to “industrial” or “conventional” agriculture (Sumberg and Giller, 2022), such as regenerative agriculture and agroecology are gaining momentum, as noticeable from the rising number of scientific papers dealing with these topics (Giller et al., 2021b; Wezel and Jauneau, 2011). Success stories of farmers in the tropics who shift away from mineral fertilizers, pesticides, and other chemical inputs also abound on social media and communication materials of nongovernmental organizations. These are increasingly being populated with testimonies of farmers diversifying their cropping systems with cover crops, investing in livestock keeping, producing high-quality compost, and improving their cropland with the use of legumes, often with claims of great positive impact on income, food security, and soil fertility maintenance.

These promises of diversified and “fully-integrated” farming systems where the need for external inputs to sustain soil fertility and crop productivity is reduced or eliminated, along with abundant scientific literature on the farm-level impact of resource recycling and improved efficiency, have certainly inspired the “input reduction” principle of agroecology: “Reduce or eliminate dependency on purchased inputs and substitute conventional inputs that have negative impacts on the environment, replacing them by making use of agroecological alternatives” (Wezel et al., 2020).

Agroecology can be defined in numerous ways. A broad definition is “the science of the relationships of organisms in an environment purposely transformed by man for crop or livestock production” (Martin and Sauerborn, 2013). More recently, agroecology has been defined as the application of ecological concepts and principles to optimize interactions between plants, animals, humans and the environment while taking into consideration the social aspects that need to be addressed for a sustainable and fair food system (Wezel et al., 2020). A key focus has been increased reliance on knowledge and management of ecological processes, complementing and reducing the use of external inputs, like mineral fertilizers and pesticides. Agroecology revolves around a set of 10 elements (FAO, 2018) or 13 principles (HLPE, 2021), among which the recycling, input reduction, soil health, biodiversity and synergy principles are directly relevant to soil fertility maintenance.¹ These principles can be operationalized through a wide range of agroecological practices, among which are intercropping, agroforestry, rotation with legumes and crop–livestock integration. Decades of scientific work in the tropics have shown that these agroecological practices can contribute to replenishing and maintaining soil fertility, i.e., “the ability of a soil to sustain plant growth by providing essential plant nutrients and favorable chemical, physical,

and biological characteristics as a habitat for plant growth” (<https://www.fao.org/global-soil-partnership/areas-of-work/soil-fertility/en/>).

Here, we question the “input reduction” principle of agroecology: what does it mean in resource-limited farming contexts, such as those commonly experienced by smallholder farmers throughout sub-Saharan Africa (SSA)?

The aforementioned success stories often seem based on conducive individual circumstances, for example, high remittances and above-average farm size, thus neglecting the constraints faced by the majority of smallholder farmers in SSA. Farm sizes have been shrinking in SSA, and soils are generally nutrient-depleted, due to low inherent fertility and decades of continuous cropping with low nutrient inputs, leading to low crop productivity (Sanchez, 2002). Huge productivity gains need to be achieved to match a growing food demand (van Ittersum et al., 2016). Yet, in the development community, particularly in SSA, an emerging viewpoint considers the use of mineral fertilizers as “climate stupid.”² Advocates of this perspective argue that governments should stop subsidizing them, due to their rising costs and their negative impact on the environment, including the emission of greenhouse gases (GHGs). Instead, they advocate for the promotion of low-cost agroecological alternatives that are expected to revitalize the soil and protect the ecosystem. Within the scientific literature, there is a debate at the science-policy interface harnessing current knowledge to build views on the possible future of agricultural systems: some authors claim that there is “a growing consensus that sustainable intensification in Africa will be [...] fertilizer intensive” (Jayne et al., 2019; Vanlauwe et al., 2014), while others assert, that “reducing the dependency on purchased inputs can reduce food insecurity especially for small-scale food producers” (Wezel et al., 2020) and that “the challenges farmers face can be met with appropriate management [...] making the addition of external inputs largely unnecessary” (Gliessman, 2014). Côte et al. (2022) propose a reconciling view of agroecology that does not exclude “the use of [...] exogenous inputs when yield gap is important,” insisting that “an in-depth agroecological transformation [...] should be free of synthetic pesticides and should be parsimonious in the use of synthetic fertilizers.” Donor agencies, notably the European Union and its member countries, increasingly support development projects in SSA that engage with the agroecological transition and transition to green economies (DG DEVCO, 2020), without necessarily being clear on the role that external inputs and mineral fertilizer play.

In this article, we critically examine the input reduction claim made by agroecology in the context of smallholder farmers in SSA. Our objective is to evaluate the feasibility and desirability of this principle for SSA, specifically concerning the maintenance of soil fertility and the role of

mineral fertilizer. Our analysis leads to five arguments: (i) the starting point in Africa is “agroecological” by default, meaning very low fertilizer use, that has over the years led to poor soil fertility as a result of widespread soil nutrient mining, (ii) the nitrogen (N) required by crops cannot be adequately fulfilled solely through biological N fixation from legumes or through recycling of animal manure, (iii) other nutrients like phosphorus (P) and potassium (K) need to be replaced and are also key for biological N fixation, (iv) mineral fertilizer, if used appropriately, causes little harm to the environment, and (v) reducing the use of mineral fertilizer would hamper crop productivity gains and contributes indirectly to agricultural expansion. We then discuss the role that agroecological principles can play in improving soil health and nutrient use efficiency, and in sustaining crop productivity.

Our analyses focus on rainfed annual cropping systems in SSA. This category regroups the maize crop-livestock, root and tuber crop, and cereal-root crop-livestock farming systems (Dixon et al., 2001) that predominate on the continent. Our analysis does not focus on irrigated systems (e.g., rice, vegetables) and perennial systems (e.g., coffee, cocoa, oil palm), that represent a relatively smaller share of the agricultural production area (Vanlauwe et al., 2023).

Starting point in SSA: Agroecological “by default”

Maintaining soil fertility through agroecological practices has been a common feature of mixed crop-livestock farming systems in SSA where livestock plays a great role in soil fertility maintenance. For example, in the cotton basin of southern Mali, the income earned from cotton production has been used by farmers to increase the size of their cattle herd—they can recycle amounts of manure as high as three tons per hectare per year (Falconnier et al., 2015). Farmers also rely on legumes and biological N fixation: in central Senegal, farmers have cultivated millet in rotation with groundnut for decades (Noba et al., 2014). Across the semiarid and sub-humid zones of the continent, from the groundnut basin of central Senegal and the cotton basin of southern Mali, to central Ethiopia (Sida et al., 2018) and the mid-Zambezi valley in Zimbabwe (Baudron, 2011), farmers have deliberately retained native trees in their fields, creating the so-called “parklands.” Some of these trees are N-fixing trees, for example, the well-known *Faidherbia albida* (Delile) A. Chev. (Peltier, 1996). In the Sahel region, farmers have traditionally maintained long-term fallows that help replenish soil fertility and offer an additional source for livestock nutrition and manure production (Schlecht et al., 2004).

As a result of these long-standing agroecological practices, manure and biological N fixation have been estimated to be the largest sources of N input to cropland when considering the African continent as a whole (Billen et al., 2014). In fact, Africa is the only region of the world where mineral fertilizer is not the first source of N input to cropland (Billen et al., 2014). This conclusion also holds when looking at N inputs to cropland at the farm and village level: despite considerable variations among

farms in, e.g., Kenya, Uganda, Ethiopia, and Mali, organic inputs from outside the farm/village are the primary source of N, followed by biological N fixation, atmospheric deposition and mineral fertilizer, in that order (Figure 1). The main sources of P input to cropland in Africa are manure and mineral fertilizer, which contribute approximately the same amount, around 2.5 kg P/ha/year. This is in contrast to the other regions of the world where the main P source is mineral fertilizer (>10 kg P/ha/year) (Ringeval et al., 2017).

Fertilizer use on cropland (including perennials) is currently very low in SSA, on average 13 kg N/ha/year, 3 kg P/ha/year, and 3 kg K/ha/year (FAOSTAT, 2023). This contrasts sharply with other regions of the world, e.g., Northern America with 73, 11, and 21 kg/ha/year for N, P, and K, and China with 170, 29, and 54 kg/ha/year for N, P, and K, respectively. The numbers for Africa mask, however, a great diversity across countries and agroecological regions within countries (Vanlauwe et al., 2023). In Africa, fertilizers are predominantly used in horticultural systems and large commercial farms, whereas their use is extremely limited in smallholder farms. Southern Africa has witnessed a sharper increase in mineral fertilizer use in the 1960s compared with East and West Africa, possibly because of the thriving large-scale farm sector in the region. In the 1980s, the phasing-out of governmental subsidies for inputs, as a result of structural adjustment programs, has caused mineral fertilizer use to decrease in several countries of SSA (Jayne et al., 2018).

One could therefore argue that smallholder mixed crop-livestock farming systems across SSA do not need to engage in an “agroecological” transition, given their limited dependency on external inputs in the form of mineral fertilizer, and their reliance on biological N fixation and recycling of plant biomass. Yet, a close look at the nutrient balances of cropping systems across the region suggests that long-term agro-environmental sustainability is not granted. Soil nutrient mining is widespread: Smaling et al. (1997) estimated that the cultivated land in SSA was losing annually 22 kg of N, 2.5 kg of P, and 15 kg of K per hectare. These negative balances have continued to increase over time (Vanlauwe et al., 2023). A comprehensive literature review indicated that more than 75% of nutrient balance studies across SSA concluded on negative balances for N and K, and about 60% of studies for P (Cobo et al., 2010). Long-term experiments conducted across the region also point to substantial soil nutrient mining over time; even the biennial rotation system of millet and groundnut in the *F. albida* parklands in central Senegal has shown evident negative N and P balances (Pieri, 1989). Similarly, the millet cropping system of western Niger with fallowing and strong livestock-mediated nutrient transfers was found to lose nutrients (Powell et al., 2004). The nutrient inputs derived from agroecological processes, as currently harnessed by smallholder farmers in SSA, combined with the current low fertilizer use, cannot compensate for nutrient exports and losses, that mainly occur in the form of crop harvest products, animal removals, leaching, and soil erosion. Demographic pressure and the related cropland expansion at the expense of rangelands and fallows add

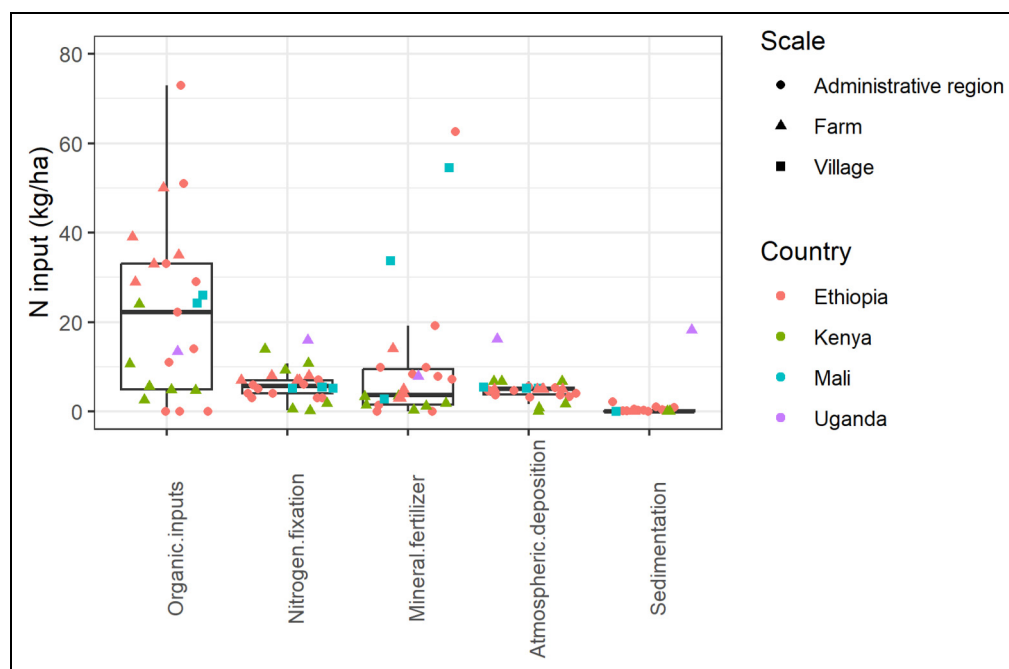


Figure 1. Sources of nitrogen (N) input to farming system (kg/ha/yr) in five selected studies across sub-Saharan Africa. Ethiopia: Hailelassie et al. (2005) and Hailelassie et al. (2007); Kenya: Gachimbi et al. (2005) and Onduru and Preez (2007); Mali: Ramisch (2005); Uganda: Nkonya et al. (2005).

further constraints on soil fertility maintenance with current agroecological practices (Schlecht et al., 2004).

This happens in the context of low crop yields compared to the yield potential that could be achieved based on the region's climate and soil properties (Affholder et al., 2013). This discrepancy can be largely attributed to low nutrient availability in the soils (Sanchez, 2002). Yields need to substantially increase to meet the current and future food demand and alleviate rural poverty in SSA while minimizing deforestation and other forms of land-use change. Narrowing yield gaps in SSA can contribute to increasing food security at household, national, and continental levels (Gérard et al., 2020; Giller et al., 2021a; van Ittersum et al., 2016). For example, modest increases in maize yield were found to greatly contribute to improved food security in Tanzania and Uganda, though this depended strongly on local contexts (Falconnier et al., 2023). Yet, increases in cereal productivity can only be achieved if nutrient inputs increase substantially (ten Berge et al., 2019). Across several case studies, the estimated maize grain yields that are compatible with food security ranged from 3.5 to 11.9 t/ha (median 6.5 t/ha, Table 1). This translates into N uptake (grain + straw) that ranges from 54 to 228 kg N/ha, with a median of 113 kg N/ha (Table 1 and Figure 2A). For a maize-based cropping system to be sustainable, these crop exports need to be compensated by some form of nutrient inputs. If mineral fertilizers were to be reduced as per the "input reduction" claim of agroecology, other forms of input need to be drastically increased. In the next sections, we examine to what extent legumes and biological N fixation, and the recycling of plant biomass through composting and use of cattle manure, can help bring the N, P, and K required.

The nitrogen needs of crops cannot be sufficiently met solely through biological nitrogen fixation by legumes and recycling of animal manure

Most legumes obtain N from the atmosphere through a symbiotic relationship with rhizobia bacteria. Plant N originating from biological fixation, if not exported from the field, is a net input to the soil-crop system. Four types of legumes can be distinguished: trees and shrubs, green manures (i.e., legumes primarily cultivated for biomass to be incorporated into the soil), grain legumes (legumes primarily cultivated for food), and fodder legumes (legumes primarily cultivated to provide feed and fodder to livestock). Figures 2B–C clearly demonstrate that on average, the potential net input from biological N fixation is greatest for legume trees and shrubs, and green manures, followed by grain legumes and fodder legumes. In what follows we scrutinize the constraints to fully achieve high levels of net N inputs with the integration of legumes into cropping systems.

Nitrogen fixation by trees and shrubs

Legume trees and shrubs could contribute as much as 100 kg N/ha/year through N fixation (median of 13 studies, Figure 2B). The net N inputs vary considerably, owing to the way perennials are integrated into cropping systems, and which plant parts are left on or incorporated into the soil (Figure 2B). Trees and shrubs can be integrated into cropping systems in at least three different ways. The first is improved woody legume fallows (Sileshi et al., 2008), where trees are planted to give a

Table 1. Estimated* nitrogen (N), phosphorus (P), and potassium (K) uptake by maize (in grain + straw) (kg/ha) for grain yield (kg/ha) compatible with food security in four selected studies.

Study	Scale	Objective	Countries	Target yield	Maize yield target (15% moisture)	Nutrient uptake* (grain + straw)		
						N	P	K
Falconnier et al. (2018)	Case studies	Household food self-sufficiency and living income	Mali	80% of water-limited yield	5447	105	13	70
Falconnier et al. (2023)	Country	Increase in household food availability	Tanzania	Profit-maximizing yield	3538	68	9	45
			Uganda	Profit-maximizing yield	2784	54	7	36
Van Ittersum et al. (2016)	Country	Country food self-sufficiency	Burkina Faso	50% of Water-limited yield	4412	85	11	57
			Ghana	80% of water-limited yield	9412	181	23	121
			Mali	50% of water-limited yield	5353	103	13	69
			Nigeria	80% of water-limited yield	10259	197	25	132
			Ethiopia	50% of water-limited yield	8824	170	21	113
			Kenya	80% of water-limited yield	5941	114	14	76
			Tanzania	80% of water-limited yield	7059	136	17	90
			Uganda	80% of water-limited yield	6682	129	16	86
			Zambia	80% of water-limited yield	11859	228	29	152
Giller et al. (2021)	Case studies	Household food security	Ethiopian Highland	Attainable yield**	7059	136	17	90
			Northern Tanzania	Attainable yield**	5882	113	14	75
			Northern Ghana	Attainable yield**	4118	79	10	53
			Cotton Basin Mali	Attainable yield**	5882	113	14	75
			Central Malawi	Attainable yield**	5882	113	14	75

*To compute N, P, and K uptake, the target maize yield was divided by an estimated maize nutrient use efficiency (in kg grain per kg crop nutrient uptake) with balanced crop nutrition as in Janssen et al. (1990) and ten Berge et al. (2019).

**Maximum crop yield observed in on-farm experiments under optimal management and input application.

large amount of high-quality biomass that can be incorporated into the soil to release nutrients for the subsequent crop. Improved fallows usually take two years to be implemented and can be considered a short-term benefit for soil fertility, but with a strong trade-off with food security because food crops cannot be grown during the fallow period. Labor for planting trees and weeding can also be a constraint to the adoption of these systems by farmers (Giller, 2001). A second option to integrate trees are parklands, i.e., the deliberate retention of scattered trees in farmers' field so that mature trees coexist with crops. In the parklands of the Sahel region, it is common to find *F. albida* trees, that shed their leaves during the growing

season, so that competition with the annual crop for light, water and nutrients is limited (Sida et al., 2018). However, only mature trees aged 20–40 years fix substantial amounts of N (Giller, 2001), which makes it a long-term investment for farmers. Although more observations are needed, net N inputs from parklands seem also lower than those from improved woody legume fallows (Figure 2B). Besides, there is a threshold beyond which the increase in tree density in parklands no longer benefits the crop (Leroux et al., 2020). A third option is alley cropping, where trees or shrubs are planted in rows alongside the crops, and their prunings can be left on or incorporated into the soil (Sileshi et al., 2011). Farmers' adoption of

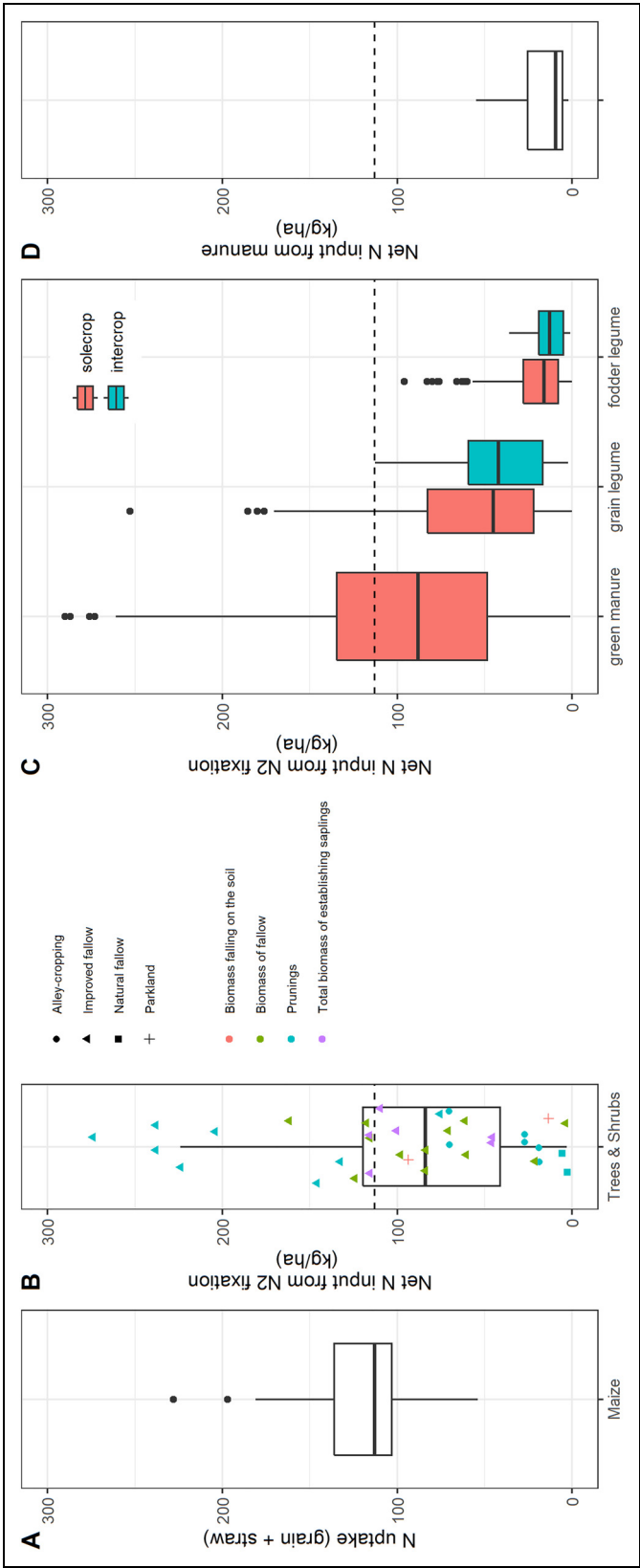


Figure 2. Boxplot of (A) estimated maize nitrogen (N) uptake (in grain + straw) for grain yield compatible with food security in four selected studies (see Table 1 for details of the four studies), (B) Net N input from biological N fixation from trees (13 studies), (C) Net N input from biological N fixation from green manures (21 studies), grain legumes (59 studies) and fodder legumes (60 studies), (D) Net N input from manure (four studies). For grain legumes, we assumed that all grain was exported and only stover was returned to the field, with a harvest index of 0.4 for soybean and groundnut and 0.35 for other grain legumes (Herridge et al., 2008). For fodder legumes, the studies are the same as for green manure (excluding those that are not palatable), but we assumed that only roots were returned to the soil. N fixed in roots was estimated using a root: shoot ratio of 0.3 for the majority of studies where it was not quantified. The dotted horizontal bar in B, C, and D is the median maize uptake (see A). In B, two outliers are not displayed (1063 and 1026 kg/ha, Peoples et al., 1996). See Table S1 for details on the reviewed studies.

alley cropping has been generally low (e.g., Swinkels and Franzel, 1997), unless employed on contours and used as fodder (see section on fodder legumes). Although alley cropping offers the prospect of alleviating the trade-off between food security and environmental sustainability, because food crops and trees can be mixed, trees often compete strongly with the crops for light and water, especially during dry years (Rao et al., 1991).

Nitrogen fixation by green manures, grain and fodder legumes

Green manures have similar potential net N inputs to cropland compared with trees and shrubs (median of 91 kg N/ha/year across 20 studies, Figure 2C). Although green manures rotated with cereals can bring a substantial yield benefit to the cereal (e.g., Ripoche et al., 2021), this comes at the cost of foregoing a part of the cereal yield, similar to woody fallows. The increase in cereal yield from the green manure often does not sufficiently compensate for this yield penalty (e.g., Ojiem et al., 2014; Ranaivoson et al., 2022). The small farm sizes exacerbate the challenge of losing a growing season for cereals, thereby becoming a major obstacle to the adoption of green manures. This concern has been very often voiced by farmers, along with the lack of consumable or marketable products derived from green manures (Vanlauwe et al., 2003). Additional labor is also another constraint, as incorporating the biomass from green manure into the soil can take as much as 80 persons per day per ha for a prolific *Mucuna* in Malawi (Vanlauwe and Giller, 2006), i.e., 40 times more than what is required to apply mineral N fertilizer (Ojiem et al., 2014).

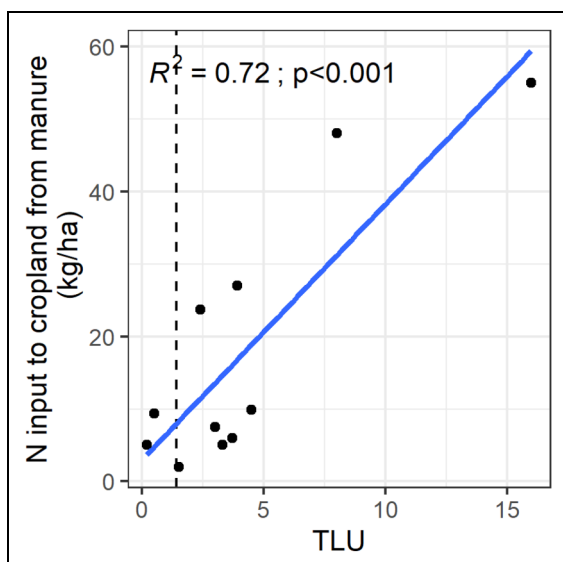


Figure 3. Nitrogen (N) input to cropland in the form of manure as a function of Topical Livestock Unit (TLU) ownership (four studies with 11 observations). The vertical dotted line is the mean value for TLU for a nationally representative sample of 6638 agricultural household in Uganda and Tanzania (LSMS-ISA data, Kilic et al., 2015).

Grain legumes offer directly consumable and marketable products, e.g., the grains of cowpea, soybean, common beans, and groundnut and are therefore preferred by farmers over woody fallows and green manures. However, the benefits in terms of soil fertility are smaller because the grains are removed from the field (Figure 2C). Franke et al. (2018) showed that on average grain legumes increase cereal yield by 0.49 t ha⁻¹ via their precrop effects. Such yield increase is considerable, but far below the strong cereal yield increases needed to reach food security in SSA (see the first section). There is a strong trade-off between legume grain yield and the residual soil nutrient benefits (Giller et al., 1994). High-yielding soybean varieties with high N-harvest index can even be “net removers” of soil N (Vanlauwe and Giller, 2006). Overall, the grain productivity of legumes is far below that of cereals, for a labor demand that is generally greater (Ojiem et al., 2014), which is a major impediment to the adoption of grain legumes by smallholder farmers.

Plant residues, including prunings from shrubs and trees, as well as the stems and leaves of grain legumes, are often of great value as fodder for livestock (except some green manures with toxic components like in some species of *Crotalaria*). For example, farmers in East Africa adopted the cultivation of fodder shrubs like *Leucaena trichandra* on contours (Wambugu et al., 2011). However, with fodder legumes, all aboveground biomass is exported from the fields, and only roots remain, representing a small N source for the following crop (Figure 2C). On the other hand, part of the fodder biomass and its nutrients can be returned to the field in the form of manure (see the section on manure).

Nitrogen fixation in intercropping with grain legumes

Grain legume intercropping can be a promising alternative to cereal-legume rotations, as it allows for the maintenance of cereal production. Although the proportion of N uptake by the legumes through biological fixation is usually similar in intercropping compared with sole cropping (e.g., Namatsheve et al., 2020), the absolute amounts, and the potential net inputs to the cropping system, are smaller (Figure 2C). This is due to the lower plant density of the legume in intercropping compared with the sole cropping, but also because of competition for light and water with the cereal crop (e.g., Traoré et al., 2022). For example, Namatsheve et al. (2020) found that the grain productivity of intercropped cowpeas was on average around 50% of that of sole cowpeas, whereas the yields of the intercropped cereals were around 80% of those of the sole crops.

Sustaining high cereal productivity through biological N fixation?

Only the legume options that compete strongly with food production (woody fallows and green manure) can bring

substantial N inputs from biological N fixation (Figure 2B) in the range of what would offset the N exports (grain + straw) of a maize crop with a yield level (~ 6.5 t/ha) that is compatible with food security objectives (Figure 2A). Other options that compete less with food production and/or offer direct value for farmers (grain and fodder legumes, Figure 2C) can only bring a fraction of what would be required to offset the N exports by maize.

The estimated contributions of biological N fixation to the net N inputs to cropland, as shown in Figure 2, are possibly overestimated. Firstly, this is because only a small fraction (less than 30%) of the N in green manure and legume tree prunings is effectively recovered by the following cereal crop. Part of it can be leached, volatilized or immobilized by soil microorganisms (Giller and Cadisch, 1995). Secondly, high levels of N fixation can only be achieved if P is not limiting, and if appropriate inoculation is performed when the legume nodulates poorly. These conditions are usually observed in on-station and/or researcher-managed trials (corresponding to most of the estimates of Figure 2) but do not necessarily hold true in farmers' fields. Thirdly, pests and diseases, usually controlled in research experiments, are an additional barrier in farmers' fields that must be overcome for the full realization of the potential benefits of legume N fixation.

In conclusion, although legumes can contribute substantially to N input to cropping systems, it is unlikely that they alone can sustain agricultural productivity at the high level that is required for food security.

Greater amounts of manure are not achievable based on herd size and fodder resources

A simple calculation indicates that about 9 t manure (dry matter) per ha per year would be required to balance the N exports by a maize crop yielding 6.5 t/ha with a corresponding export of 125 kg N/ha in its grain and stover (see Table 1), considering that manure from smallholder farms in SSA contains on average 1.4% N (Pieri, 1989). This is largely beyond the 4 t/ha typically applied by cattle owners on a portion of their cropland in, e.g., Zimbabwe (Rusinamhodzi et al., 2013; Zingore et al., 2008). Nine Tropical Livestock Units (TLU), corresponding to approximately 13 cattle or 90 goats, are required to produce 9 t of manure (considering that one TLU produces 2.8 kg of manure per day, Berre et al., 2021). This number of TLU is far beyond what smallholder farmers typically own: for example, the average TLU across nationally representative household samples (Living Standards Measurement Study—Integrated Surveys on Agriculture, LSMS-ISA data) was 1.39 in Uganda and 1.43 in Tanzania (Figure 3). Because it is not feasible to collect all the produced manure and part of its N is lost during storage, composting and transport (Vayssières and Rufino, 2012), farmers recycle far less than what is theoretically possible. Even farmers owning 12 TLU or more cannot recycle the required 125 kg N/ha (Figure 3). Thus, recycling of N through manure falls short of what is required to sustain the necessary levels of cereal yields (Figure 2A, 2D).

During the cropping season, livestock cannot access fields and feed mainly on rangelands. One TLU—250 kg liveweight—consumes a maximum of 3% of its liveweight daily (Moran, 2005). Based on a simple calculation, it is estimated that 1.4 ha of rangeland would be required for feeding one TLU in the Sudano-Sahelian environment of West Africa, corresponding to a livestock carrying capacity of 0.7 TLU/ha. This estimation assumes that one TLU requires around 1400 kg of biomass over a six-month growing season and that rangelands produce about 1000 kg of biomass (dry matter) per hectare with 600 mm of rainfall, considering a rainfall productivity of 1.7 kg biomass (dry matter) per millimeter rain (Rufino et al., 2011). In many areas of the Sudano-Sahelian region, livestock density is far beyond this estimated carrying capacity of 0.7 TLU/ha, e.g., 4.8 TLU/ha in western Burkina Faso (Andrieu et al., 2015) and 1.3 TLU/ha in the Senegalese groundnut basin (Grillot et al., 2018). It is also important to note that high grazing pressure often leads to a decline in rangeland productivity (Hiernaux et al., 2009). The above estimations indicate that available feed resources are a strong constraint to maintaining the large herds that would be necessary to produce the manure required to sustain high cereal yields. Furthermore, manure represents a direct transfer of nutrients from rangelands to croplands. For example, Andrieu et al. (2015) estimated that N loss from the rangeland could be as high as 25 kg N/ha/year in western Burkina Faso. Enriching cropland with nutrients from manure therefore comes at the expense of soil nutrient mining in rangelands (Powell et al., 2004).

Phosphorus and potassium need to be imported and replaced continually

For P and K fertilization, agroecological practices rely on the transfers of biomass through manure and compost. It should, however, be noted that with these lateral transfers, the places of origin of the biomass (e.g., rangelands, hedgerows, fields of farmers who do not own cattle and where crop residues are left) are progressively impoverished in P and K. Therefore, we argue that P and K need to be brought by mineral fertilizers if long-term agro-environmental sustainability is to be guaranteed.

In addition, biomass transfers are also often insufficient to meet crop requirements. One reason is that low P and K contents in soil translate into low P and K concentrations in recycled plant materials. Soils of SSA have typically low plant-available P due to low P concentration in the parent material and extended weathering, and because of low soil pH and binding of phosphates by Fe^{3+} and Al^{3+} cations (Margenot et al., 2016). Similarly, plant-available K in soils of SSA is generally low because of prolonged weathering over time and insufficient external inputs (Majumdar et al., 2021).

As a result, P and K concentrations in manure and compost are rarely above respectively 0.2 and 0.6%, in SSA (Blanchard et al., 2014; Fall et al., 2000; Zingore

et al., 2008). This means that manure inputs of respectively 8 and 14 t/ha would be required to sustain a maize yield of 6.5 t/ha, corresponding to P and K uptake demands of 16 kg P ha⁻¹ and 83 kg K ha⁻¹. It is clear that these P and K requirements for crops are difficult or even impossible to achieve by smallholder farmers, given their current herd sizes and feed resource limitations (see previous section and Schlecht et al., 2004).

Relying solely on biomass transfers in combination with the ongoing depletion of soil P and K might also have implications for the potential of legumes to efficiently fix N. In particular, insufficient availability of P can constrain biological N fixation, as adenosine triphosphate is needed in larger quantities for N-fixing legumes than for other crops (Giller, 2001). Besides, soil K deficiency affects the growth of rhizobia, nodule formation and functioning, resulting in a depressing effect on biological N fixation (Divito and Sadras, 2014).

If produced differently and used appropriately, mineral fertilizers cause little harm to the environment

Mineral fertilizers are often and rightly blamed for environmental pollution (Gruber and Galloway, 2008). Pollution arises from both their use and their production. In what follows, we analyze opportunities to address the negative environmental outcomes of mineral fertilizer, firstly related to their use, and secondly to their production.

In general, fertilizer use contributes to four negative environmental outcomes. First, direct soil emission from the application of mineral fertilizers is the most important source of N₂O emission from agriculture, together with emissions from organic fertilizer (Tian et al., 2020). The estimations regarding these two emission sources carry considerable uncertainty, making it challenging to distinctly differentiate between them (IPCC, 2022). Second, NH₃ volatilization from fertilizer application can have serious consequences for human health, acidification, and eutrophication of ecosystems (Liu et al., 2023; Paerl et al., 2014), and is also a source of indirect production of N₂O. Third, the global increase in N and P fertilizer use has led to the eutrophication of water (Paerl et al., 2014; Peñuelas and Sardans, 2022). Fourth, N fertilizers have resulted in global soil acidification that can undermine soil carbon (C) sequestration and climate mitigation efforts (Raza et al., 2021). Yet, these negative outcomes do not come from the fertilizers *per se*, but from their excessive or inappropriate use. It is important to note that there are no chemical differences between NH₄⁺ or NO₃⁻ ions coming from organic or mineral fertilizers. Plants equally absorb both these two ions regardless of their source while the origins of negative environmental impacts of nutrients vary. For example, N₂O emissions are very high in Europe, North America, and East and South Asia, which together consume over 80% of the world's mineral N fertilizers (Guenet et al., 2021; Tian et al., 2020), while it is manure application that is currently the main source of

agricultural N₂O emissions in SSA (Davidson, 2009; Guenet et al., 2021).

Global N-use efficiency in croplands has dramatically dropped over the last decades and is now only about 40% (Lassaletta et al., 2014; Zhang et al., 2015). The potential to improve fertilizer-use efficiency and reduce pollution in regions of intensive agriculture is therefore large, with a limited negative impact on crop yield (Wuepper et al., 2020). For example, it has been reported that N-use efficiency in Greece increased from 30% in 1990 to more than 70% in 2010 (Lassaletta et al., 2014). In SSA, the scope to improve N-use efficiency is also large, as the current average agronomic efficiency of N is estimated at 14 kg maize grain per kg N applied, compared with the global average of 30 kg kg⁻¹ (Vanlauwe et al., 2023). In general, improvement of nutrient-use efficiency can be achieved by widely adopting the 4R principles (the right nutrient source at the right rate, right time and right place) (Penuelas et al., 2023). In the context of SSA, site-specific nutrient management tailored to the high spatial heterogeneity of smallholder farming systems will be key (Chivenge et al., 2021). An analysis of 11 published studies showed that the addition of N fertilizer increased N₂O emissions compared to the no input control, but there were no differences among the different rates of N fertilizer application (Vanlauwe et al., 2023). In addition, even with the high N fertilizer rates, N₂O emissions remained below 1 kg N₂O-N ha⁻¹. Nitrogen fertilizer application at a rate four to five times greater than the current average in SSA (i.e., 60 kg N/ha), using one basal application and two top dressings, led to low N₂O emissions in Zimbabwe, far below the IPCC default values (i.e., 0.5 to 1% of applied mineral N) (Shumba et al., 2023).

With regard to production, the synthesis of NH₃ to produce mineral N fertilizers accounts for about 0.8–1.2% of the global anthropogenic CO₂ emissions and 2% of global energy (Gao and Serrenhoo, 2023; Smith et al., 2020). Ammonia emissions during fertilizer production are also responsible for indirect N₂O emissions. These GHG emissions could, however, be largely reduced by the production of NH₃ using hydrogen from water hydrolysis with renewable energy instead of fossil fuels (Smith et al., 2020; Wang et al., 2018). This prospect is currently significant enough for the IPCC to consider NH₃ as a potential low- or zero-carbon fuel similar to hydrogen (IPCC, 2022). The current expansion of fertilizer manufacturing witnessed across Africa could also largely reduce GHG emissions due to transport, besides increasing the sovereignty of the region for access to fertilizer.

Overall, it is estimated that GHG emissions from N fertilizer production and use could be reduced by up to one-fifth of current levels by 2050 with currently available technologies, increasing N-use efficiency being the most effective one, as about two-thirds of GHG emissions from fertilizers actually take place immediately after their application in croplands (Gao and Serrenhoo, 2023). The excess of fertilizers currently being used in regions where overapplication is prevalent could be redistributed to SSA (less in the Global North, more in the Global South), possibly without the need to produce more fertilizers at the global scale.

Eutrophication is a rising issue throughout Africa, particularly around large and rapidly expanding cities (Nyenje et al., 2010), but it is currently most probably driven by untreated sewage waste and erosion deposits rather than by the excessive fertilizer use in agriculture (Vanlauwe and Giller, 2006). However, if fertilizer use is to increase, its contribution to eutrophication has to be carefully monitored. Relevant “4R” fertilizer practices that are crucial to increase profitability and reduce gaseous losses will also contribute to limit N and P leaching and their contribution to eutrophication.

Reducing the use of mineral fertilizer hampers crop productivity gains and contributes indirectly to agricultural expansion

The impacts of a strategy where the use of mineral fertilizer is reduced or eliminated, as purported by the “input reduction” principle of agroecology should be carefully evaluated, and weighed against the negative environmental impacts associated with fertilizer use. Because nutrient limitations constrain crop yields (see the first section), reducing fertilizer use will further lower crop yields, and inevitably drive cropland expansion to meet the demands of a fast-growing population in SSA. Although increased fertilizer use for higher crop productivity will cause an increase in N₂O emissions (e.g., Leitner et al., 2020), cropland expansion into natural ecosystems would trigger an even greater ecological footprint. Conversion of natural ecosystems into cropland is associated with accelerated vegetation and soil C loss, and loss of biodiversity (Searchinger et al., 2015). Kehoe et al. (2017) showed greater biodiversity losses with cropland expansion than with agricultural intensification, globally and in SSA in particular. Van Loon et al. (2019) projected greater GHG emissions associated with cropland expansion than with agricultural intensification to meet food security in SSA by 2050. In addition, even though SSA is generally considered as having abundant land, accounting for about 60% of the world’s uncultivated arable land, this abundance is primarily concentrated in less than 10 countries. Most countries in the region are facing land scarcity. This makes cropland expansion a limited option, emphasizing the need for production intensification on existing cropland. For a net positive effect of intensification and fertilizer use on the GHG balance of Africa to take place, public policies and stronger governance of natural resources will have to be put in place to prevent rebound effects (i.e., increased deforestation due to increased profitability of farming) (Byerlee et al., 2014). In this context, it is noteworthy to highlight that a number of countries in the South, such as Vietnam, India, Bhutan, El Salvador and Chile, have successfully achieved a land-use transition in recent decades through sound policies and innovations, which has led to the simultaneous increase of their forest cover and agricultural production (Lambin and Meyfroidt, 2011).

Agroecological principles help improve soil health, nutrient-use efficiency and sustain crop productivity

Maintaining soil health

It is clear from what precedes that harnessing only biomass fluxes and biological N fixation cannot bring all the nutrients required to increase food production and meet the food demand of an increasing population. However, these processes and the related practices are key to maintain or improve soil health in general, and soil organic C, in particular (Vanlauwe et al., 2023). Soil health is one of the 13 HLPE principles of agroecology, and is reflected in three of the ten FAO agroecology elements, namely diversity, synergy and resilience (Wezel et al., 2020). Degraded soils, i.e., soils with poor health and with chemical and physical properties of low quality are estimated to occur in 25% of croplands globally, across all environmental conditions (Le et al., 2016). In what follows we show that two agroecology principles (recycling and biodiversity) and associated practices (the use of organic amendments and agroforestry) are key to maintain and improve soil health.

Degraded soils tend to be poorly responsive to mineral fertilizers (Nezomba et al., 2015). The application or retention of organic resources is critical to maintain or restore soil health (Laub et al., 2023). Crop residues are the most abundant and available organic resource, and their retention in croplands can play a significant role. However, due to other competing demands for animal feed, fuel and construction, amounts of crop residues returned to cropland are usually low (Valbuena et al., 2012). In this context, manure is often the most critical resource to maintain soil health, but required application rates may be prohibitive to smallholders (see section on manure). On the other hand, there is a large potential to increase the biomass and nutrients being recycled through manure by adopting better herd management (e.g., cattle housing) and improved manure storage (e.g., heap coverage) (Rufino et al., 2007). Improved recycling is thus required if soil organic matter is to be maintained in soils. Manure application can also mitigate soil acidification resulting from the continuous application of N fertilizers on soils with low cation exchange capacity and low pH buffering capacity (Vanlauwe et al., 2001).

Agroforestry—defined in its broad sense as “land-use systems and practices in which woody perennials are deliberately integrated with crops and/or animals on the same land management unit” (Leakey, 1996)—can also maintain and improve soil health. Agroforestry is based on the biodiversity principle. Compared to annuals, some perennials have deeper root systems and fix more C, capture nutrients from deeper soil layers and produce biomass and litter for a longer period of time; their inclusion in cropping systems can thus contribute to a greater input of organic C to the soil (Corbeels et al., 2019), but also lead to nutrient cycles (e.g., N, P) that are more tightly coupled to the C cycle (by stoichiometric relations in plant biomass,

organic matter and microbial biomass), and thus are less leaky (Lemaire et al., 2014).

Improving nutrient-use efficiency

Efficiency is a key principle of agroecology (captured in both 13 HLPE principles and the 10 FAO elements), but also a concept that is central to the ecological and economic sustainability of any agricultural production system, whether agroecological or not (Kumar et al., 2020).

Long-term improvement of soil health as described above can lead to more nutrients being supplied by the decomposition of soil organic matter, complementing or substituting some of the nutrients that need to be supplied by mineral fertilizers (Myers et al., 1994). Although nutrients other than N “need to be imported and replaced continually” (see section on P and K), agroecological practices help maximize their use efficiency. In the case of P in particular, the inclusion of legumes (principle of biodiversity) can lead to higher nutrient-use efficiency, as legumes tend to have greater rates of P acquisition than cereals (e.g., Tang et al., 2021). Often, the efficiency of mineral fertilizer improves with the use of agroecological practices. For example, the incorporation of *Crotalaria-Mucuna* green manures into the soil improved N-use efficiency of the subsequent upland rice in Madagascar (Ranaivoson et al., 2022); the use of cattle manure was responsible for increased maize response to mineral fertilizer in Kenyan smallholder farms (Njoroge et al., 2019); intercropping maize with soybean gave greater fertilizer N-use efficiency across 106 observations in Africa (Xu et al., 2020). More generally, experimental evidence suggests that increased plant diversity—in particular functional diversity tends to lead to higher nutrient-use efficiency (Furey and Tilman, 2021). Biomass recycling (through manure, crop residues; principle of recycling) also leads to P being retained in the labile organic soil pools, which may lead to higher P-use efficiency (Drinkwater et al., 2017). Similarly, nutrient-use efficiency was shown to be promoted by nutrient recycling through livestock grazing (e.g., Hiernaux and Turner, 1996). Finally, better nutrient-use efficiency also decreases the risk of negative cost-benefit ratios when farmers invest in fertilizers (Biélders and Gérard, 2015).

Maintaining other ecosystem services for sustained crop productivity

Bommarco et al. (2013) highlighted the link between supporting and regulating ecosystem services, crop productivity and yield gaps, both in low-input and intensively cultivated production systems. Soil fertility maintenance and nutrient cycling are key supporting ecosystem services for agriculture and have been reviewed in the previous sections of this article. Biological pest and weed control, and crop pollination are two regulating ecosystem services that are equally critical for food production.

Crop losses due to pests are projected to increase with climate change (Deutsch et al., 2018) while the use of

insecticides in agriculture is increasingly regulated and its cost-benefit ratio is declining globally (Zhang, 2018). Weeds also contribute substantially to yield gaps globally for a range of crops (maize, wheat, cotton, soybean) (Oerke, 2006). As a result, biological pest and weed control is becoming more critical, in both low-input and intensively cultivated production systems. Similarly, the global pollinator decline is threatening all regions of the world. Yield losses due to pollinator decline have been recorded globally for crops with a moderate dependence on pollination. On the other hand, yields of crops with a high dependence on pollination may have been maintained by their stronger reliance on domestic honeybees, whose stocks are, however, growing slower than the demand for pollination (Aizen and Harder, 2009; Garibaldi et al., 2009).

Biological pest and weed control, and pollination may be stimulated by increasing on-farm diversity, a key agroecology principle. For example, the populations of wild pollinators, and predatory and parasitoid arthropods may increase following the retention of natural and semi-natural patches in cropland, that provide nectar, alternative preys, and overwintering and nesting habitats (Bianchi et al., 2006). These patches may also host and provide cropland with insectivorous birds and bats (Sow et al., 2020). Natural areas may also provide agricultural areas with herbivores feeding on weeds, and with pathogens attacking crop pests (Blitzer et al., 2012). The optimal amount of noncrop habitat and the optimal spatial arrangement are species-specific, and depend on the dispersal ability and sensitivity to disturbance (including edge effects) of the species of interest (Ekroos et al., 2016). With regard to weeds, diversified crop rotations including legumes can help decrease weed pressure and its impact on cereal yield (e.g., Ripoché et al., 2021). Appropriate biological pest and weed control is a critical step to ensure appropriate crop growth and improved nutrient-use efficiency (ten Berge et al., 2019).

Conclusions

The analysis of existing scientific literature on nutrient balances in SSA, biological N fixation of tropical legumes, and manure production and use in smallholder farming systems shows that agroecological practices have a clear role to play when it comes to maintaining and improving soil fertility in the context of smallholder farmers in SSA. However, further reducing the already low use of mineral fertilizer—as per the “input reduction” principle of agroecology—may aggravate the current challenge of nutrient depletion in croplands and rangelands throughout SSA. Our analysis shows that biophysical production factors, but also shortages of land and farm labor, constrain the opportunity to close crop nutrient gaps and increase productivity by relying solely on N fixation and transfers of biomass using manure. More research at the farm and landscape level where issues of nutrient availability and sustainability operate, is needed to explore the benefits and constraints of agroecology. It is, however, clear that agroecological practices can improve nutrient-use efficiency and should complement the use of mineral

fertilizer, provided that financial and physical access to fertilizer is guaranteed through adequate market development. Moreover, effective policy support to agroecological practices that deliver great environmental benefits for the society, but often limited short-term benefits to farmers, requires urgent attention.

Author's note

François Affholder, Universidade Eduardo Mondlane, Faculdade de Agronomia e Engenharia Florestal, Maputo.

Declaration of conflicting interests

The authors declared no potential conflicts of interest with respect to the research, authorship, and/or publication of this article.

Funding

The authors disclosed receipt of the following financial support for the research, authorship, and/or publication of this article: This work was supported by the European Union's Horizon 2020 research and innovation program, deEU-DESIRA program [grant numbers 101083653, project CANALLS (Driving agroecological transitions in the humid tropics of Central and Eastern Africa through transdisciplinary agroecology Living Labs) and 424-933, project RAIZ (Promoting agroecological intensification for resilience building in Zimbabwe)].

ORCID iDs

Gatien N. Falconnier  <https://orcid.org/0000-0003-3291-650X>

Aude Ripoché  <https://orcid.org/0000-0001-6756-9777>

Ken E. Giller  <https://orcid.org/0000-0002-5998-4652>

Supplemental material

Supplemental material for this article is available online.

Notes

1. These principles encompass a set of goals that are summarize in HLPE (2021), as follows: **Recycling** aims at “Preferentially using local renewable resources to close as far as possible resource cycles of nutrients and biomass”; **Input reduction** intends to “Reduce or eliminate the dependency on purchased inputs and increasing self-sufficiency”; **Soil health** is defined as “Secure and enhance soil health and functioning for improved plant growth, particularly by managing organic matter and enhancing soil biological activity”; **Biodiversity** aims at “Maintaining and enhancing diversity of species, functional diversity and genetic resources and thereby maintaining overall agroecosystem biodiversity in time and space at field, farm and landscape scales”; **Synergy** purpose is to “Enhance positive ecological interaction, synergy, integration and complementarity among the elements of agroecosystems (animals, crops, trees, soil and water).”
2. <https://www.thecanary.co/global/world-analysis/2022/09/12/african-farmers-to-uk-stop-funding-climate-stupid-agriculture-on-our-continent/>

References

Affholder F, Poeydebat C, Corbeels M, et al. (2013) The yield gap of major food crops in family agriculture in the tropics: Assessment and analysis through field surveys and modelling. *Field Crops Research* 143: 106–118.

Aizen MA and Harder LD (2009) The global stock of domesticated honey bees is growing slower than agricultural demand for pollination. *Current Biology* 19(11): 915–918.

Andrieu N, Vayssières J, Corbeels M, et al. (2015) From farm scale synergies to village scale trade-offs: Cereal crop residues use in an agro-pastoral system of the Sudanian zone of Burkina Faso. *Agricultural Systems* 134: 84–96.

Baudron F (2011) *Agricultural intensification - Saving space for wildlife?* Thèse. Wageningen University, Wageningen. Available at: https://publications.cirad.fr/une_notice.php?dk=562980 (accessed 5 June 2023).

Berre D, Diarissio T, Andrieu N, et al. (2021) Biomass flows in an agro-pastoral village in West-Africa: Who benefits from crop residue mulching? *Agricultural Systems* 187: 102981.

Bianchi FJ, Booij CJH and Tschamtké T (2006) Sustainable pest regulation in agricultural landscapes: A review on landscape composition, biodiversity and natural pest control. *Proceedings of the Royal Society B: Biological Sciences* 273(1595): 1715–1727.

Bielders CL and Gérard B (2015) Millet response to microdose fertilization in south-western Niger: Effect of antecedent fertility management and environmental factors. *Field Crops Research* 171: 165–175.

Billen G, Lassaletta L and Garnier J (2014) A biogeochemical view of the global agro-food system: Nitrogen flows associated with protein production, consumption and trade. *Global Food Security* 3(3): 209–219.

Blanchard M, Coulibaly K, Bognini S, et al. (2014) Diversité de la qualité des engrais organiques produits par les paysans d'Afrique de l'Ouest : quelles conséquences sur les recommandations de fumure ? *BASE*. Available at: <https://popups.uliege.be/1780-4507/index.php?id=11654> (accessed 20 May 2023).

Blitzer EJ, Dormann CF, Holzschuh A, et al. (2012) Spillover of functionally important organisms between managed and natural habitats. *Agriculture, Ecosystems & Environment* 146(1): 34–43.

Bommarco R, Kleijn D and Potts SG (2013) Ecological intensification: Harnessing ecosystem services for food security. *Trends in Ecology & Evolution* 28(4): 230–238.

Byerlee D, Stevenson J and Villoria N (2014) Does intensification slow crop land expansion or encourage deforestation? *Global Food Security* 3(2): 92–98.

Chivenge P, Saito K, Bunquin MA, et al. (2021) Co-benefits of nutrient management tailored to smallholder agriculture. *Global Food Security* 30: 100570.

Cobo JG, Dercon G and Cadisch G (2010) Nutrient balances in African land use systems across different spatial scales: A review of approaches, challenges and progress. *Agriculture, Ecosystems & Environment* 136(1): 1–15.

Corbeels M, Cardinael R, Naudin K, et al. (2019) The 4 per 1000 goal and soil carbon storage under agroforestry and conservation agriculture systems in sub-Saharan Africa. *Soil and Tillage Research* 188: 16–26. DOI: 10.1016/j.still.2018.02.015.

Côte FX, Rapidel B, Sourisseau JM, et al. (2022) Levers for the agroecological transition of tropical agriculture. *Agronomy for Sustainable Development* 42(4): 67.

Davidson EA (2009) The contribution of manure and fertilizer nitrogen to atmospheric nitrous oxide since 1860. *Nature Geoscience* 2(9): 659–662.

Deutsch CA, Tewksbury JJ, Tigchelaar M, et al. (2018) Increase in crop losses to insect pests in a warming climate. *Science* 361(6405): 916–919.

DG DEVCO (2020) Strategic Plan 2020–2024 Directorate-General for International Cooperation and Development - DG DEVCO. Available at: https://commission.europa.eu/system/files/2020-10/devco_sp_2020_2024_en.pdf (accessed 5 June 2023).

- Divito GA and Sadras VO (2014) How do phosphorus, potassium and sulphur affect plant growth and biological nitrogen fixation in crop and pasture legumes? A meta-analysis. *Field Crops Research* 156: 161–171.
- Dixon J, Gulliver A, Gibbon D, et al. (2001) *Farming Systems and Poverty. Improving Farmers' Livelihoods in a Changing World*. Washington, DC: World Bank Group.
- Drinkwater LE, Schipanski M, Snapp S, et al. (2017) Chapter 7 - ecologically based nutrient management. In: Snapp S and Pound B (eds) *Agricultural Systems (Second Edition)*. San Diego: Academic Press, 203–257.
- Ekroos J, Ödman AM, Andersson GKS, et al. (2016) Sparing land for biodiversity at multiple spatial scales. *Frontiers in Ecology and Evolution* 3. Available at: <https://www.frontiersin.org/articles/10.3389/fevo.2015.00145> (accessed 15 September 2022).
- Falconnier GN, Descheemaeker K and Traore B (2018) Agricultural intensification and policy interventions: Exploring plausible futures for smallholder farmers in Southern Mali. *Land Use Policy* 70: 623–634.
- Falconnier GN, Descheemaeker K, Van Mourik TA, et al. (2015) Understanding farm trajectories and development pathways: Two decades of change in southern Mali. *Agricultural Systems* 139: 210–222.
- Falconnier GN, Leroux L, Beillouin D, et al. (2023) Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa. *Agricultural Systems* 205: 103588.
- Fall ST, Fall AS, Cissé I, et al. (2000) Intégration horticulture – élevage dans les systèmes agricoles urbains de la zone des Niayes (Sénégal). *Bulletin de l'APAD* 19: 19.
- FAO (2018) *The 10 Elements of Agroecology: Guiding the Transition to Sustainable Food and Agricultural Systems*. Rome, Italy: FAO. Available at: <https://www.fao.org/documents/card/en/c/I9037EN/> (accessed 21 May 2023).
- FAOSTAT (2023) Food and Agriculture Organization of the United Nations. Rome, Italy. <http://faostat.fao.org> ((accessed May 2023)). Available at: <http://faostat.fao.org/site/567/DesktopDefault.aspx?PageID=567#ancor> (accessed 14 February 2016).
- Franke AC, van den Brand GJ, Vanlauwe B, et al. (2018) Sustainable intensification through rotations with grain legumes in Sub-Saharan Africa: A review. *Agriculture, Ecosystems & Environment* 261: 172–185.
- Furey GN and Tilman D (2021) Plant biodiversity and the regeneration of soil fertility. *Proceedings of the National Academy of Sciences* 118(49): e2111321118.
- Gachimbini LN, Keulen H, Thurairaja EG, et al. (2005) Nutrient balances at farm level in Machakos (Kenya), using a participatory nutrient monitoring (NUTMON) approach. *Land Use Policy, Soil Degradation in Sub-Saharan Africa* 22: 13–22.
- Gao Y and Serrenhoo AC (2023) Greenhouse gas emissions from nitrogen fertilizers could be reduced by up to one-fifth of current levels by 2050 with combined interventions. *Nature Food* 4(2): 170–178.
- Garibaldi LA, Aizen MA, Cunningham SA, et al. (2009) Pollinator shortage and global crop yield. *Communicative & Integrative Biology* 2(1): 37–39.
- Gérard F, Affholder F, Mane NF, et al. (2020) Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal. In: *Impact de différentes politiques publiques sur l'intensification agroécologique et les inégalités de revenu dans le Bassin arachidier du Sénégal*. Papiers de recherche. Paris Cedex 12: Agence française de développement, pp. 1–76.
- Giller KE (2001) *Nitrogen Fixation in Tropical Cropping Systems*. New York: CABI Publishing. DOI:10.1016/0378-4290(93)90012-c
- Giller KE and Cadisch G (1995) Future benefits from biological nitrogen fixation: An ecological approach to agriculture. *Plant and Soil* 174(1): 255–277.
- Giller KE, Delaune T, Silva JV, et al. (2021a) Small farms and development in sub-Saharan Africa: Farming for food, for income or for lack of better options? *Food Security* 13(6): 1431–1454. DOI: 10.1007/s12571-021-01209-0.
- Giller KE, Hijbeek R, Andersson JA, et al. (2021b) Regenerative agriculture: An agronomic perspective. *Outlook on Agriculture* 50(1): 13–25.
- Giller KE, McDonagh JF and Cadisch G (1994) Can biological nitrogen fixation sustain agriculture in the tropics? In: Syers JK and Rimmer BL (eds) *Soil Science and Sustainable Land Management in the Tropics*. Wallingford: CAB International, pp. 173–191.
- Gliessman SR (2014) *Agroecology: The Ecology of Sustainable Food Systems*. 3rd ed. Boca Raton: CRC Press.
- Grillot M, Guerrin F, Gaudou B, et al. (2018) Multi-level analysis of nutrient cycling within agro-sylvo-pastoral landscapes in West Africa using an agent-based model. *Environmental Modelling & Software* 107: 267–280.
- Gruber N and Galloway JN (2008) An earth-system perspective of the global nitrogen cycle. *Nature* 451(7176): 293–296.
- Guenet B, Gabrielle B, Chenu C, et al. (2021) Can N₂O emissions offset the benefits from soil organic carbon storage? *Global Change Biology* 27(2): 237–256.
- Hailelassie A, Priess J, Veldkamp E, et al. (2005) Assessment of soil nutrient depletion and its spatial variability on smallholders' mixed farming systems in Ethiopia using partial versus full nutrient balances. *Agriculture, Ecosystems & Environment* 108: 1–16.
- Hailelassie A, Priess JA, Veldkamp E, et al. (2007) Nutrient flows and balances at the field and farm scale: Exploring effects of land-use strategies and access to resources. *Agricultural Systems* 94: 459–470.
- Herridge DF, Peoples MB and Boddey RM (2008) Global inputs of biological nitrogen fixation in agricultural systems. *Plant and Soil* 311: 1–18.
- Hiernaux P, Ayantunde A, Kalilou A, et al. (2009) Trends in productivity of crops, fallow and rangelands in Southwest Niger: Impact of land use, management and variable rainfall. *Journal of Hydrology* 375(1–2): 65–77.
- Hiernaux P and Turner MD (1996) The effect of clipping on growth and nutrient uptake of Sahelian annual rangelands. *Journal of Applied Ecology* 33(2): 387–399.
- HLPE (2021) HLPE Report #14 - Agroecological and other innovative approaches for sustainable agriculture and food systems that enhance food security and nutrition.: 163.
- IPCC (2022) Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. In: Shukla PR, Skea J, Slade R, et al. (eds). Cambridge, UK and New York, NY, USA: Cambridge University Press, p. 2042. Available at: <https://www.ipcc.ch/report/ar6/wg3/> (accessed 5 June 2023).
- Janssen BH, Guiking FCT, van der Eijk D, et al. (1990) A system for quantitative evaluation of the fertility of tropical soils (QUEFTS). *Geoderma* 46: 299–318.
- Jayne TS, Mason NM, Burke WJ, et al. (2018) Review: Taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy* 75: 1–14.

- Jayne TS, Snapp S, Place F, et al. (2019) Sustainable agricultural intensification in an era of rural transformation in Africa. *Global Food Security* 20: 105–113.
- Kehoe L, Romero-Muñoz A, Polaina E, et al. (2017) Biodiversity at risk under future cropland expansion and intensification. *Nature Ecology & Evolution* 1(8): 1129–1135.
- Kilic T, Winters P and Carletto C (2015) Gender and agriculture in sub-Saharan Africa: Introduction to the special issue. *Agricultural Economics* 46: 281–284.
- Kumar S, Meena RS and Jhariya MK (eds) (2020) *Resources Use Efficiency in Agriculture*. Singapore: Springer.
- Lambin EF and Meyfroidt P (2011) Global land use change, economic globalization, and the looming land scarcity. *Proceedings of the National Academy of Sciences* 108(9): 3465–3472.
- Lassaletta L, Billen G, Grizzetti B, et al. (2014) 50 year trends in nitrogen use efficiency of world cropping systems: The relationship between yield and nitrogen input to cropland. *Environmental Research Letters* 9(10): 105011. DOI: 10.1088/1748-9326/9/10/105011.
- Laub M, Corbeels M, Couëdel A, et al. (2023) Managing soil organic carbon in tropical agroecosystems: Evidence from four long-term experiments in Kenya. *SOIL* 9(1): 301–323.
- Le QB, Nkonya E and Mirzabaev A (2016) Biomass productivity-based mapping of global land degradation hotspots. In: Nkonya E, Mirzabaev A and von Braun J (eds) *Economics of Land Degradation and Improvement – A Global Assessment for Sustainable Development*. Cham: Springer International Publishing, 55–84.
- Leakey RRB (1996) Definition of agroforestry revisited. *Agroforestry Today (ICRAF)*. Available at: https://scholar.google.com/scholar_lookup?title=Definition+of+agroforestry+revisited&author=Leakey%2C+R.R.B.+%28ICRAF%2C+Nairobi+%28Kenya%29%29&publication_year=1996 (accessed 21 May 2023).
- Leitner S, Pelster DE, Werner C, et al. (2020) Closing maize yield gaps in sub-Saharan Africa will boost soil N₂O emissions. *Current Opinion in Environmental Sustainability* 47: 95–105.
- Lemaire G, Franzluebbers A, Carvalho PCF, et al. (2014) Integrated crop–livestock systems: Strategies to achieve synergy between agricultural production and environmental quality. *Agriculture, Ecosystems & Environment* 190: 4–8.
- Leroux L, Falconnier GN, Diouf AA, et al. (2020) Using remote sensing to assess the effect of trees on millet yield in complex parklands of Central Senegal. *Agricultural Systems* 184: 102918.
- Liu L, Xu W, Wen Z, et al. (2023) Modeling global oceanic nitrogen deposition from food systems and its mitigation potential by reducing overuse of fertilizers. *Proceedings of the National Academy of Sciences* 120(17): e2221459120.
- Majumdar K, Norton RM, Murrell TS, et al. (2021) Assessing potassium mass balances in different countries and scales. In: Murrell TS, Mikkelsen RL, Sulewski G, et al. (eds) *Improving Potassium Recommendations for Agricultural Crops*. Cham: Springer International Publishing, 283–340.
- Margenot AJ, Singh BR, Rao IM, et al. (2016) Phosphorus fertilization and management in soils of Sub-Saharan Africa. In: Lal R and Stewart BA (eds) *Soil Phosphorus*. London: Taylor and Francis group, pp. 58.
- Martin K and Sauerborn J (2013) *Agroecology*. Dordrecht: Springer Netherlands.
- Moran J (2005) *Tropical Dairy Farming: Feeding Management for Smallholder Dairy Farmers in the Humid Tropics*. Collingwood: Landlinks Press, p.312
- Myers RJK, Palm CA, Cuevas E, et al. (1994) The synchronisation of nutrient mineralisation and plant nutrient demand. In: Woomer PL and Swift MJ (eds) *The Biological Management of Tropical Soil Fertility*. Chichester (GBR); Londres: J. Wiley; Sayce, pp. 81–116. ISBN 0-471-95095-5.
- Namatsheve T, Cardinael R, Corbeels M, et al. (2020) Productivity and biological N₂-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa: A review. *Agronomy for Sustainable Development* 40(4): 30. DOI: 10.1007/s13593-020-00629-0.
- Nezomba H, Mtambanengwe F, Titttonell P, et al. (2015) Point of no return? Rehabilitating degraded soils for increased crop productivity on smallholder farms in eastern Zimbabwe. *Geoderma* 239–240: 143–155.
- Njoroge S, Schut AGT, Giller KE, et al. (2019) Learning from the soil's memory: Tailoring of fertilizer application based on past manure applications increases fertilizer use efficiency and crop productivity on Kenyan smallholder farms. *European Journal of Agronomy* 105: 52–61.
- Nkonya E, Kaizzi C and Pender J (2005) Determinants of nutrient balances in a maize farming system in eastern Uganda. *Agricultural Systems* 85: 155–182.
- Noba K, Ngom A, Guèye M, et al. (2014) L'arachide au Sénégal : État des lieux, contraintes et perspectives pour la relance de la filière. *OCL* 21(2): D205.
- Nyenje P, Foppen J, Uhlenbrook S, et al. (2010) Eutrophication and nutrient release in urban areas of sub-Saharan Africa—a review. *The Science of the Total Environment* 408(3): 447–455. DOI: 10.1016/j.scitotenv.2009.10.020.
- Oerke E-C (2006) Crop losses to pests. *The Journal of Agricultural Science* 144(1): 31–43.
- Ojiem JO, Franke AC, Vanlauwe B, et al. (2014) Benefits of legume–maize rotations: Assessing the impact of diversity on the productivity of smallholders in Western Kenya. *Field Crops Research* 168: 75–85.
- Onduru DD and Preez CC (2007) Ecological and agro-economic study of small farms in sub-Saharan Africa. *Agronomy for Sustainable Development* 27: 197–208.
- Paerl HW, Gardner WS, Mccarthy MJ, et al. (2014) Algal blooms: Noteworthy nitrogen. *Science* 346(6206): 175.
- Peltier R (ed) (1996) *Les parcs à faidherbia*. Montpellier: CIRAD-Forêt. Available at: <https://agritrop.cirad.fr/326407/> (accessed 15 May 2023).
- Penuelas J, Coello F and Sardans J (2023) A better use of fertilizers is needed for global food security and environmental sustainability. *Agriculture & Food Security* 12(1): 5.
- Peñuelas J and Sardans J (2022) The global nitrogen-phosphorus imbalance. *Science* 375(6578): 266–267.
- Peoples MB, Palmer B, Lilley DM, et al. (1996) Application of 15N and xylem ureide methods for assessing N₂ fixation of three shrub legumes periodically pruned for forage. *Plant and Soil* 182: 125–137.
- Pieri C (1989) Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricoles au Sud du Sahara. Montpellier: CIRAD-IRAT, p. 452 ISBN 2-87614-024-1.
- Powell JM, Pearson RA and Hiernaux PH (2004) Crop–livestock interactions in the West African drylands. *Agronomy Journal* 96(2): 469–483.
- Ramisch JJ (2005) Inequality, agro-pastoral exchanges, and soil fertility gradients in southern Mali. *Agriculture, Ecosystems & Environment* 105: 353–372.
- Ranaivoson L, Falconnier GN, Affholder F, et al. (2022) Can green manure contribute to sustainable intensification of rainfed rice production in Madagascar? *Field Crops Research* 289: 108711.
- Rao MR, Ong CK, Pathak P, et al. (1991) Productivity of annual cropping and agroforestry systems on a shallow Alfisol in semi-arid India. *Agroforestry Systems* 15(1): 51–63.

- Raza S, Zamanian K, Ullah S, et al. (2021) Inorganic carbon losses by soil acidification jeopardize global efforts on carbon sequestration and climate change mitigation. *Journal of Cleaner Production* 315: 128036.
- Ringeval B, Augusto L, Monod H, et al. (2017) Phosphorus in agricultural soils: Drivers of its distribution at the global scale. *Global Change Biology* 23(8): 3418–3432.
- Ripoche A, Autray P, Rabary B, et al. (2021) Increasing plant diversity promotes ecosystem functions in rainfed rice based short rotations in Malagasy highlands. *Agriculture, Ecosystems & Environment* 320: 107576.
- Rufino MC, Dury J, Titttonell P, et al. (2011) Competing use of organic resources, village-level interactions between farm types and climate variability in a communal area of NE Zimbabwe. *Agricultural Systems* 104(2): 175–190.
- Rufino MC, Titttonell P, van Wijk MT, et al. (2007) Manure as a key resource within smallholder farming systems: Analysing farm-scale nutrient cycling efficiencies with the NUANCES framework. *Livestock Science* 112(3): 273–287.
- Rusinamhodzi L, Corbeels M, Zingore S, et al. (2013) Pushing the envelope? Maize production intensification and the role of cattle manure in recovery of degraded soils in smallholder farming areas of Zimbabwe. *Field Crops Research* 147: 40–53.
- Sanchez PA (2002) Soil fertility and hunger in Africa. *Science* 295(5562): 2019–2020.
- Schlecht E, Hiernaux P, Achard F, et al. (2004) Livestock related nutrient budgets within village territories in western Niger. *Nutrient Cycling in Agroecosystems* 68(3): 199–211.
- Searchinger TD, Estes L, Thornton PK, et al. (2015) High carbon and biodiversity costs from converting Africa's wet savannahs to cropland. *Nature Climate Change* 5(5): 481–486.
- Shumba A, Chikowo R, Corbeels M, et al. (2023) Long-term tillage, residue management and crop rotation impacts on N₂O and CH₄ emissions from two contrasting soils in sub-humid Zimbabwe. *Agriculture, Ecosystems & Environment* 341: 108207.
- Sida TS, Baudron F, Kim H, et al. (2018) Climate-smart agroforestry: *Faidherbia albida* trees buffer wheat against climatic extremes in the Central Rift Valley of Ethiopia. *Agricultural and Forest Meteorology* 248: 339–347.
- Sileshi G, Akinnifesi FK, Ajayi OC, et al. (2008) Meta-analysis of maize yield response to woody and herbaceous legumes in sub-Saharan Africa. *Plant and Soil* 307(1): 1–19.
- Sileshi GW, Akinnifesi FK, Ajayi OC, et al. (2011) Integration of legume trees in maize-based cropping systems improves rain use efficiency and yield stability under rain-fed agriculture. *Agricultural Water Management* 98(9): 1364–1372.
- Smaling EMA, Nandwa SM and Janssen BH (1997) Soil fertility in Africa is at stake. In: Buresh RJ, Sanchez PA and Calhoun F (eds) *Replenishing Soil Fertility in Africa*. Madison, Wisconsin: John Wiley & Sons, Ltd, 47–61. <https://onlinelibrary.wiley.com/doi/abs/10.2136/sssaspecpub51.c2> (accessed 15 May 2023).
- Smith C, Hill K and Torrente-Murciano L (2020) Current and future role of Haber–Bosch ammonia in a carbon-free energy landscape. *Energy and Environmental Science* 13: 331–344.
- Sow A, Seye D, Faye E, et al. (2020) Birds and bats contribute to natural regulation of the millet head miner in tree-crop agroforestry systems. *Crop Protection* 132: 105127.
- Sumberg J and Giller KE (2022) What is 'conventional' agriculture? *Global Food Security* 32: 100617.
- Swinkels R and Franzel S (1997) Adoption potential of hedgerow intercropping in maize-based cropping systems in the highlands of Western Kenya 2. Economic and farmers' evaluation. *Experimental Agriculture* 33(2): 211–223.
- Tang X, Zhang C, Yu Y, et al. (2021) Intercropping legumes and cereals increases phosphorus use efficiency; a meta-analysis. *Plant and Soil* 460(1): 89–104.
- ten Berge HFM, Hijbeek R, van Loon MP, et al. (2019) Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Global Food Security* 23: 9–21.
- Tian H, Xu R, Canadell JG, et al. (2020) A comprehensive quantification of global nitrous oxide sources and sinks. *Nature* 586: 248–255.
- Traoré A, Falconnier GN, Ba A, et al. (2022) Modeling sorghum-cowpea intercropping for a site in the savannah zone of Mali: Strengths and weaknesses of the Stics model. *Field Crops Research* 285: 108581.
- Valbuena D, Erenstein O, Homann-Kee Tui S, et al. (2012) Conservation agriculture in mixed crop–livestock systems: Scoping crop residue trade-offs in Sub-Saharan Africa and South Asia. *Field Crops Research* 132: 175–184.
- van Ittersum MK, van Bussel LGJ, Wolf J, et al. (2016) Can sub-Saharan Africa feed itself? *Proceedings of the National Academy of Sciences of the United States of America* 113(52): 14964–14969.
- Van Ittersum M K, Van Bussel Lgj and Wolf J (2016) Can sub-Saharan Africa feed itself?. *Proceedings of the National Academy of Sciences of the United States of America* 113(52): 14964–14969.
- Vanlauwe B, Amede T, Bationo A, et al. (2023) Fertilizer and soil health in Africa: The role of fertilizer in building soil health to sustain farming and address climate change. IFDC. Available at: <https://agritrop.cirad.fr/604248/> (accessed 15 May 2023).
- Vanlauwe B, Bationo A, Carsky RJ, et al. (2003) Enhancing the contribution of legumes and biological nitrogen fixation in cropping systems: Experiences from West Africa. In: Waddington SR (ed) *Grain Legumes and Green Manures for Soil Fertility in Southern Africa: Taking Stock of Progress*. Harare, Zimbabwe: Soil Fert Net and CIMMYT-Zimbabwe, p. 246.
- Vanlauwe B and Giller KE (2006) Popular myths around soil fertility management in sub-Saharan Africa. *Agriculture, Ecosystems & Environment* 116(1–2): 34–46.
- Vanlauwe B, Wendt J and Diels J (2001) Combined application of organic matter and fertilizer. In: Tian G, Ishida F and Keatinge J (eds) *Sustaining Soil Fertility in West-Africa*. SSSA Special Publication Number 58, pp. Madison, Wisconsin: John Wiley & Sons, pp. 247–280. DOI:10.2136/sssaspecpub58.c12.
- Vanlauwe B, Wendt J, Giller KE, et al. (2014) A fourth principle is required to define conservation agriculture in sub-Saharan Africa: The appropriate use of fertilizer to enhance crop productivity. *Field Crops Research* 155: 10–13.
- van Loon MP, Hijbeek R, Berge HFM, et al. (2019) Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Global Change Biology* 25(11): 3720–3730.
- Vayssières J and Rufino MC (2012) Managing nutrient cycles in crop and livestock systems with green technologies. In: Boye JJ and Arcand Y (eds) *Green Technologies in Food Production and Processing*. Food Engineering Series. Boston, MA: Springer US, pp. 151–182.
- Wambugu C, Place F and Franzel S (2011) Research, development and scaling-up the adoption of fodder shrub innovations in East Africa. *International Journal of Agricultural Sustainability* 9(1): 100–109.

- Wang L, Xia M, Wang H, et al. (2018) Greening ammonia toward the solar ammonia refinery. *Joule* 2(6): 1055–1074.
- Wezel A, Herren BG, Kerr RB, et al. (2020) Agroecological principles and elements and their implications for transitioning to sustainable food systems: A review. *Agronomy for Sustainable Development* 40(6): 40.
- Wezel A and Jauneau J-C (2011) Agroecology – interpretations, approaches and their links to nature conservation, rural development and ecotourism, pp. 1–25. DOI:10.1007/978-94-007-1309-3_1.
- Wuepper D, Le CS, Zilberman D, et al. (2020) Countries influence the trade-off between crop yields and nitrogen pollution. *Nature Food* 1(11): 713–719. DOI: 10.1038/s43016-020-00185-6.
- Xu Z, Li C, Zhang C, et al. (2020) Intercropping maize and soybean increases efficiency of land and fertilizer nitrogen use; A meta-analysis. *Field Crops Research* 246: 107661.
- Zhang W (2018) Global pesticide use: Profile, trend, cost / benefit and more. *Proceedings of the International Academy of Ecology and Environmental Sciences* 1: 1–27.
- Zhang X, Davidson EA, Mauzerall DL, et al. (2015) Managing nitrogen for sustainable development. *Nature* 528(7580): 51–59.
- Zingore S, Delve RJ, Nyamangara J, et al. (2008) Multiple benefits of manure: The key to maintenance of soil fertility and restoration of depleted sandy soils on African smallholder farms. *Nutrient Cycling in Agroecosystems* 80(3): 267–282.



Sustainable intensification of sorghum-based cropping systems in semi-arid sub-Saharan Africa: The role of improved varieties, mineral fertilizer, and legume integration

Amadou Traore^a, Gatien N. Falconnier^{b,c,d,f,*}, Antoine Couëdel^{b,c}, Benjamin Sultan^e,
Vimbayi G.P. Chimonyo^d, Myriam Adam^{h,i,j}, François Affholder^{b,c,g}

^a IER (Institut d' Economie Rurale), Mali

^b AIDA, Univ Montpellier, CIRAD, Montpellier, France

^c CIRAD, UPR AIDA, F-34398 Montpellier, France

^d International Maize and Wheat Improvement Centre (CIMMYT)-Zimbabwe, 12.5 km Peg Mazwe Road, Harare, Zimbabwe

^e ESPACE-DEV, Univ Montpellier, IRD, Univ Guyane, Univ Reunion, Univ Antilles, Univ Avignon, France

^f University of Zimbabwe, Harare, Zimbabwe

^g Universidade Eduardo Mondlane, Faculdade de Agronomia e Engenharia Florestal, Maputo, Mozambique

^h National University of Battambang, Battambang Province 021402, Kingdom of Cambodia

ⁱ Centre de Coopération Internationale en Recherche Agronomique Pour le Développement (CIRAD), UMR AGAP Institut, Montpellier, France

^j UMR AGAP Institut, Univ Montpellier, CIRAD, INRAE, Institut Agro, Montpellier, France

ARTICLE INFO

Keywords:

Stics
Intercropping
Fertilizer
Yield variability
Sorghum
Cowpea

ABSTRACT

Problem: Sustainable intensification of cereal cropping systems can contribute to reducing food insecurity while mitigating biodiversity losses thanks to land sparing. Yet, intensifying crop production with more nutrient inputs often increases sensitivity to climate hazards and yields inter-annual variability. How different options for sustainable intensification interact and how they could help achieve greater and less variable yields is not well known for key cereal cropping systems of sub-Saharan Africa.

Objective: Here, we aim to assess the impact on productivity and its interannual variation of three contrasted strategies of crop intensification, namely i) the integration of cowpea intercropped with sorghum or as sole crop, ii) improved varieties with high harvest index and greater nitrogen use efficiency, and iii) the use of more mineral fertilizer.

Methods: We did this assessment using a calibrated soil-crop model for a case study of sorghum-based cropping systems of semi-arid southern Mali, using a historical weather series from 1980 to 2010.

Results: We found that the incremental combinations of two or three strategies helped increase productivity in terms of energy and protein. However, greater productivity went hand in hand with greater inter-annual variability. Intercropping sorghum with cowpea helped to reduce the inter-annual variability of productivity, but only when mineral fertilizer was not added. With mineral fertilizer input, sorghum contributed the largest share of the intercrop productivity, and sorghum yield was more variable from a year to another than cowpea yield. The overall productivity of intercropping sorghum with cowpea was always greater than having the two sole crops on separate plots. This was possible thanks to the facilitation of light, water and N acquisition by the two crops in the intercropping, regardless of the specificities of the growing season with regard to water and nitrogen stress. However, the variability of productivity was smaller for the cultivation of the two sole crops on separate plots, regardless of fertilizer input.

Conclusion: The often-claimed benefit of intercropping on reducing the inter-annual variability of production does not hold when the three strategies are combined.

Implications: Our results suggest that the integration of legumes does not help cushion farmers against the risk related to the intensification of cropping systems with more nutrients and improved seeds. Careful gross margin analysis that accounts for price variability and uncertainty would be required to refine this risk assessment for

* Correspondence to: CIRAD, UPR AIDA, Harare, Zimbabwe.

E-mail address: gatien.falconnier@cirad.fr (G.N. Falconnier).

<https://doi.org/10.1016/j.fcr.2023.109180>

Received 11 May 2023; Received in revised form 20 October 2023; Accepted 28 October 2023

Available online 6 November 2023

0378-4290/© 2023 Elsevier B.V. All rights reserved.

specific farm contexts. We discuss the implication of these findings in light of the current research agenda for the sustainable intensification of cropping systems in sub-Saharan Africa.

1. Introduction

Africa's burgeoning population and plateauing low agricultural yields due to low nutrient stocks in soils pose significant challenges to food and nutrition security (FAO et al., 2022; van Ittersum et al., 2016). Meeting the continent's food demand while sparing the natural land required for biodiversity conservation requires substantially boosting cereal crop yields (van Loon et al., 2019; ten Berge et al., 2019).

Sustainable intensification technologies offer the prospect of increasing the productivity of cereal-based cropping systems. There are three main entry points for sustainable intensification. Legumes are the first key entry point through their unique ability to fix atmospheric nitrogen. Legumes can be integrated into cereal-based cropping systems in several ways. Intercropping, the cultivation of two plant species during an overlapping time of the growing season, is one of them. In tropical cereal-legume intercropping, the legume usually does not suffer too much from the light competition brought by the cereal, can extract some of the soil water not available for the cereal (Baldé et al., 2011), and usually obtain almost half of its nitrogen through biological nitrogen fixation (Namatsheve et al., 2021). It was found that cereal-legume intercropping increased overall yield by 26–42% compared to sole cropping (Namatsheve et al., 2020) on average across 60 studies across sub-Saharan Africa. Cereal-legume intercropping is also expected to decrease yield inter-annual variability compared with sole crops due to different water and heat stress sensitivity. Despite these benefits, implementing intercropping can be challenging for farmers. In mechanized systems, harvesting may be much more complicated, and even in manual agriculture, harvesting the legume under the canopy of the cereal can be tedious (Falconnier, 2016). The legume may not provide a sufficient cover to suppress weed growth and, at the same time, hampers hand or mechanical weeding (Ganeme et al., 2021). Due to higher sowing densities, sole legumes generally achieve greater yield than their intercropped counterpart, thus providing larger residual N to the subsequent cereal when residues are retained in the field (Mupangwa et al., 2021; Thierfelder et al., 2012). These are among the possible reasons why farmers cultivating cereal and legumes may prefer to use sole crops and rotate them with cereals.

Another way of sustainably intensifying these systems is by using improved cereal varieties - a second relevant entry point. In SSA, less than 50% of rural farmers can access improved cereal cultivars (Sheahan and Barrett, 2017). The majority of farmers either use recycled seeds or traditional varieties. Although traditional varieties are well adapted to local conditions and possess desirable traits for stress tolerance, yields are often low (Frankin et al., 2021). Local cultivars often have a low harvest index, are less responsive to nitrogen fertilizers and are prone to lodging (Frankin et al., 2021). Significant cereal breeding investments targeting rainfed environments in Africa have been occurring to increase productivity and reduce food and nutrition security. Improved varieties usually have greater harvest index and yield potential than farmers' local cereal cultivars (Kante et al., 2019). Nitrogen use efficiency of these improved cultivars is also usually greater than traditional ones (Vanlauwe et al., 2011).

The third critical entry point is mineral fertilizer. Despite recent input subsidy programs for fertilizer, current fertilizer availability and use in SSA are low (Jayne et al., 2018). The low subsidies added to the poor inherent fertility of the weathered soils across the continent, and the low availability of cattle manure creates widespread nutrient limitations for cereal growth (Falconnier et al., 2023a; Folberth et al., 2013). In most soils, mineral fertilizers bring immediate yield benefits to the cereal, substantially impacting household and regional food security (Falconnier et al., 2023b; Pieri, 1989; Ripoché et al., 2015). There are

many reasons why mineral fertilizer use is currently low in sub-Saharan Africa. These include low crop response to fertilizer due to inadequate crop management (ten Berge et al., 2019), meso and micronutrient deficiencies (Njoroge et al., 2017) and risk of unprofitable returns (Jayne et al., 2018) due to constraining cost of fertilizer (Bonilla Cedrez et al., 2021). Achieving food security by 2050 in Africa with the use of fertilizer was found to emit less GHGs than a strategy based on maintaining the current low yield and expanding cropland (van Loon et al., 2019).

These three entry points for sustainable intensification form part of 'integrated soil fertility management' (ISFM), and a combination of these options, tailored to the local context of the farmer, is required to reach 'full ISFM' (Vanlauwe et al., 2015, 2014). These options help bring more nutrients to the cereal and alleviate nutrient stresses. However, mounting evidence shows that when nutrient stress is released, cereals are more sensitive to climate hazards like drought and heat stress (Adam et al., 2020; Affholder, 1997; Falconnier et al., 2020). Intensification with more nutrients then comes with greater inter-annual variations of production – a major cause of concern for farmers who are often risk-averse (Jourdain et al., 2020). Farmers run the risk of unprofitable returns when investing in the inputs required for sustainable intensification (e.g. seed, fertilizer) (Biélers and Gérard, 2015). Going 'beyond averages' when assessing the performance of a combination of sustainable intensification options is thus critical (Vanlauwe et al., 2019). Yield variability, i.e. the measurement of yield inter-annual-variations in response to a given crop management, must be assessed carefully. To date, analysis of yield variability in intercropping and crop rotation is mainly assessed using field experiments during a limited number of years – usually two to four years (Chimonyo et al., 2019; Peter and Runge-Metzger, 1994; Raseduzzaman and Jensen, 2017). Such short-term experiments do not allow the adequate capture of risk associated with climate inter-annual variability (e.g. how often is drought observed in a series of two to four experimental years likely to happen in a 20-year historical climate series?). Robustly calibrated crop models are expected to help with that assessment. The analysis of simulated yield variability for a combination of improved varieties and mineral fertilizer input has yielded crucial insights on optimal planting date, varietal choice and input to minimize risk for cereal production in a tropical environment (Amouzou et al., 2019; Huet et al., 2022). However, so far, there has been minimal modelling work on the impact of the integration of legumes on the productivity and variability of cereal-based cropping systems.

In this paper, we seized the opportunity to use the recent advances in our capacity to model legume and cereal growth as sole and intercrops with the STICS soil-crop model (Ranaivoson et al., 2022; Traoré et al., 2022). We focused on the case study of southern Mali with the example of sorghum and cowpea. In this typical land-constrained area, farmers face uncertainties in crop production related to the variability of the semi-arid climate (Traore et al., 2013a), and where diversification with legumes offers the prospect to contribute to food security (Falconnier et al., 2018, 2017). We used the calibrated Stics model and a virtual experiment with historical observed climate (1980–2010) to explore the following main research question:

How do three options for sustainable intensification (integration of legume, variety, fertilizer) interact to achieve greater and less variable sorghum yields in the face of current inter-annual climate variability? This general question was decomposed into two sub-questions: i) does intercropping help decrease the sensitivity of crop production to climate inter-annual variability, and how do the sorghum variety and fertilizer input interact with this potential advantage? and ii) does intercropping with legume provide greater agronomic benefits (greater and less variable yields) than its integration as a sole crop?

Our leading hypothesis is that sorghum and cowpea sensitivity to climate hazards is different, and legume integration (as sole or intercrop) helps decrease the inter-annual variability of crop production.

2. Materials and methods

2.1. Study area

The study area is the old cotton basin in the Koutiala region of Mali. This region hosts about 40% of the Malian population and 50% of the arable land (Traore et al., 2013b). The climate of southern Mali is typical of the Sudano-Sahelian zone of West Africa. The rainy season extends from May to October. Annual rainfall varies between 480 and 1250 mm, and seasonal average temperature is 28 °C (1980–2010). Agricultural systems in the region are mixed agro-sylvo-pastoral systems. Cotton (*Gossypium hirsutum* L.) is the main cash crop, cultivated in rotation with cereals such as maize (*Zea mays* L.), millet (*Pennisetum glaucum* (L.) R. Br.), sorghum (*Sorghum bicolor* (L.) Moench) and legumes such as groundnut (*Arachis hypogaea* L.) and cowpea (*Vigna unguiculata* (L.) Walp.). In this study, we focused on sorghum and cowpea as an example of typical cereals and legumes in the Sudano-Sahelian zone of West Africa.

2.2. The stics crop model

Stics is a process-based soil-crop model that simulates daily interactions between the water, carbon, and nitrogen cycles as a function of crop species, management (such as sowing, soil preparation, irrigation, mineral and organic fertilization, residue management), and pedoclimatic characteristics (daily weather, soil texture, C and N organic content) (Brisson et al., 2009). Stics simulates potential yield (limited by temperature and solar radiation) and water and N-limited yields by accounting for water and N stresses. Stics has been calibrated and tested for different type of cereals (e.g. winter wheat, maize, barley, sorghum) and legumes (e.g. pea, fababean, cowpea) (Coucheney et al., 2015; Falconnier et al., 2019; Taroré et al., 2022).

Stics has also been adapted to simulate intercropping (Brisson et al., 2004). It simulates competition between two species for light, water and nitrogen. Competition for light occurs between a main cultivated species (the cereal in our study) and an understorey one (cowpea in our case) thanks to a complex energy transfer module that accounts for crop extinction coefficient, row spacing and canopy shape (Brisson et al., 2004). Stics calculates water and nitrogen uptake in intercropping, accounting for the distribution of the roots of each cultivated species along the soil profile. Water requirements are computed with a daily time step applying the resistance network analogy to account for the microclimatic effect between the two species (Shuttleworth and Wallace, 1985). Water stress reduces growth through reduced radiation use efficiency and transpiration (Brisson et al., 2009). Nitrogen uptake depends on N availability in soil, root density (depth and distribution) and the crop nitrogen demand. Nitrogen stress impacts growth through reduced radiation conversion efficiency to biomass and leaf area (reducing radiation interception efficiency). Stics also simulate actual atmospheric N₂ fixation by legumes as a function of soil water content, soil temperature, and soil mineral nitrogen used to compute water, temperature, and N stresses that decrease potential fixation. A more detailed description of the plant-plant interactions at play in intercropping in Stics can be found in Brisson et al. (2004) and for the specific case of sorghum-cowpea intercropping in Traoré et al. (2022).

2.3. Model calibration and evaluation

The model calibration and evaluation data originated from a sorghum-cowpea experiment conducted in 2017 and 2018 at the N'Tarla experimental station (12.6193°N, -5.689°W). The impact of four factors was investigated: i) cropping system (sole cropping or

intercropping), ii) sorghum variety (a local variety sensitive to photoperiod V1, and an improved variety less sensitive to photoperiod, with greater harvest index and N use efficiency, V2), iii) fertilization (no nitrogen input, and 38 kg/ha nitrogen input, corresponding to local recommendation to farmers by extension services), and iv) sowing date of sorghum (early vs late). Cowpea was planted two weeks after sorghum. Soil organic N averaged across the plot used for model calibration was 0.012%. For the intercropping treatment, the design was additive; that is, intercropped sorghum had the same planting density as the sole crop (62500 plants/ha), while cowpea planting density was 70% of the density of the sole crop (88888 plants/ha).

The cowpea variety investigated was a dual-purpose variety (grain for human consumption and fodder for animal feed). Sorghum and cowpea dates of emergence, beginning of grain filling and physiological maturity were recorded for sole and intercropping plots. Leaf area index (LAI) was measured six to seven times for sole and intercropping plots during the growing season. In 2018, soil volumetric water content was measured with a Diviner 2000 probe in each experimental plot (sole and intercropping) along the soil profile every 10 cm down to 150 cm deep, two to three times per week during the cropping season. The crops were harvested after physiological maturity, and total above-ground biomass and grain yield were determined. The experimental setup and measurements are described in detail in Traoré et al. (2022). In 2018, the combination of sorghum variety, cropping system, sowing date and fertilization defined 17 cropping situations (16 sorghum situations and one sole cowpea situation) used for model calibration. In 2017, there was only one fertilizer level, and treatment combinations led to 8 cropping situations used for model evaluation. Observations for calibration included crop phenology, in-season soil moisture, in-season LAI, above-ground biomass and plant N, and grain yield and number of grains at harvest. Soil data used for model initialisation included pH, C/N ratio of soil organic matter, and total topsoil nitrogen. Soil and plant parameters were calibrated following a stepwise calibration procedure described in detail in Traoré et al. (2022). Model performance was quantified by calculating the relative root mean square error (rRMSE) and model efficiency (EF, Willmott et al., 1985) for above-ground biomass, plant nitrogen uptake, number of grains and grain yield at the end of the growing season. The ability of the Stics model to reproduce the direction and the order of magnitude of the changes in above-ground biomass and grain yield related to the experimental factors (fertilization, variety, intercropping with cowpea) was also assessed.

For model calibration in this study, we started with the soil and plant parameters calibrated by Traoré et al. (2022). The calibration of the study of Traoré et al. (2022) had the primary objective of identifying the causes of differences between cropping situations in the field experiment each year. However, the calibration did not satisfactorily reproduce the differences in observed variables between years of the experiments, though simulation analysis pointed to differences in climate between the two years as a main cause. In the current study, we further calibrated the model to better reproduce the differences between cropping situations in a given year and the impact of inter-annual weather variability on water stress. We used the same procedure as in the previous study but changed one parameter previously left at its default value in the study cited above: the parameter *rsm* (the minimal stomatal resistance of leaves) governing plant transpiration for sorghum. After this new calibration, model accuracy was satisfactory for a range of variables (Figure S1), and simulations reproduced the impact of intercropping, variety and fertilizer on sorghum and cowpea above-ground biomass and yield (Figure S2). The model predicted little competition of cowpea on sorghum for radiation and water and somewhat stronger competition for nitrogen, but this did not translate into a substantial yield penalty for the sorghum as partial Land Equivalent Ratio (pLER) values for above-ground biomass (AGB) and grain yield remained close to one (Figure S4). On the contrary, the model predicted a strong sorghum competition on cowpea for light, water, and nitrogen, which translated

into a strong yield penalty for cowpea as pLER values were below 0.7 (Figure S4). Overall, the intercropping simulated LER (considering light, water, nitrogen, above-ground biomass, and grain yield) was consistently above one, indicating a benefit of the intercropping over the sole crop (Figure S4).

2.4. Virtual experiment

2.4.1. Eight options for sustainable intensification

Eight options for sustainable intensification of sorghum-based cropping systems were simulated with the crop model in a virtual experiment. Option 1 represented current farmers' practices (Table 1 and Fig. 1): growing the local sorghum variety as a sole crop without N application is indeed a common practice of farmers in the area. Three innovative practices for sustainable intensification were investigated: improved sorghum variety, mineral fertiliser, and integration of cowpea with intercropping. In the virtual experiment, we used the sorghum varieties that were calibrated using the field experiment data (see Section 2.2). The intercropping additive design of the field experiment was also considered for this virtual experiment. For mineral fertiliser, the application of 150 kgN/ha (assumed to cover the needs of sorghum and alleviate any N stress, <https://www.yieldgap.org/gygaviewer/index.html>) was explored in comparison with the null application in farmers' current practice. We did not intend to explore the impact of N input that was economically feasible. The aim was to explore contrasting fertility treatments influencing sorghum sensitivity to climate stresses. These options were tested in isolation (options 2, 3 and 4), combined two by two (5, 6, 7) and eventually combined altogether (option 8) [Fig. 1]. Options 2–8 (Table 1) encompass increasing levels of complexity and portray different possible steps towards sustainable intensification (Vanlauwe et al., 2014). Options 2, 5, 7 and 8 had a "bis" version where legume integration was done with sole cropping rather than intercropping (Table 1). For this integration of sole legume, we assumed that one ha plot would be divided into 0.5 ha of sole sorghum (62500 plants/ha) and 0.5 ha of sole cowpea (88888 plants/ha).

2.4.2. Weather and simulation settings

Daily rainfall, minimum and maximum temperatures, duration of solar brightness (converted to global radiation), relative humidity and windspeed were recorded at the N'Tarla meteorological station about 100 m from the experimental field used for model calibration and

evaluation. We used the climatic record from 1980 to 2010 for the virtual experiment. The calibrated Stics soil-crop model was used to assess the performance of the crop management options (Table 1) with historical weather data (1980–2010). Eight simulation units were constructed, corresponding to the eight main cropping options of Table 1. The 'bis' version of Option 2, 5, 7 and 8 corresponded to 8 additional simulation units – four for sole sorghum and four for sole cowpea. We initialized soil water at the wilting point one month prior to sowing. Initial soil mineral Nitrogen was assumed to be zero. The simulations were reset each year so that water and nutrient carry-overs from one year to another were not considered.

2.5. Analysis of the performance of options

To compare sole and intercrop options, we determined the productivity of the eight options in terms of energy and protein, considering sorghum, an energy content of 3290 kcal kg⁻¹ and a protein content of 106 g/kg (USDA, 2023a), and for cowpea an energy content of 3360 kcal kg⁻¹, and a protein content of 235 g/kg (USDA, 2023b).

For each option, we computed the 31-year median energy productivity and its interquartile range (IQR). Because the implementation of options involves additional investment (labour, seeds and/or fertiliser) compared with current farmers' practice, options with greater variability (greater IQR) can be risky and lead to unfavourable cost-benefit ratios (see an example in Figure S3). A convenient indicator of climate-related risk of agricultural activities is the probability that yield gets below the yield target corresponding to a favourable cost-benefit ratio (see e.g. Rötter et al., 1997). However, determining thresholds for favourable cost-benefit ratios depend on farmers' objectives and on outputs and inputs prices. To evaluate the influence of our cropping system options on climate related risk as depending exclusively on biophysical factors, we compared the magnitude of yield variations in response to inter-annual variations of climate. Therefore we chose to use the interquartile range of the yield distribution (IQR), because it does not require any assumptions on farmers objectives and input/output prices. The coefficient of variation (CV, standard deviation divided by the mean) is another way of looking at yield variability. However, it is inflated for low input systems (low average yield) and deflated for intensive systems because of greater yield. Using Waddington et al. (2007) experimental data, we found that CV is 81% for treatment without fertilizer (F0) and 68% with fertilizer (F1). Based on this CV,

Table 1

Description of the actual crop management (Option 1: "current farmers practice") and seven other crop management options (2–8) tested to move towards sustainable intensification. V1 = local variety, V2 = improved variety. Options 2, 5 and 8 have a "bis" version where legume integration is done with rotation rather than intercropping.

Strategy	Number of innovative practices implemented	Option number	Option name	Description of the system	N fertilization (kg/ha)	Sorghum Variety
A	0	1	Current farmers practice	Sole local sorghum - no fertilizer	0	V1
B	1	2	Intercropping	Intercropping local sorghum with cowpea - no fertilizer	0	V1
		2bis	Integration of sole legume	Sole local sorghum with sole cowpea (0.5 ha sorghum, 0.5 ha cowpea)	0	V1
		3	Variety	Sole improved sorghum - no fertilizer	0	V2
		4	Fertilizer	Sole local sorghum with fertilizer	150	V1
C	2	5	Variety + intercropping	Intercropping improved sorghum with cowpea - no fertilizer	0	V2
		5bis	Variety + integration of sole legume	Sole improved sorghum with sole cowpea (0.5 ha sorghum, 0.5 ha cowpea)	0	V2
		6	Variety + fertilizer	Sole improved sorghum with fertilizer	150	V2
		7	Fertilizer + intercropping	Intercropping local sorghum with cowpea - fertilizer	150	V1
		7bis	Fertilizer + integration of sole legume	Sole local sorghum with fertilizer and sole cowpea	150	V1
D	3	8	Variety + fertilizer + intercropping	Intercropping improved sorghum with cowpea - fertilizer	150	V2
		8bis	Variety + fertilizer + integration of sole legume	Improved sorghum - fertilizer and sole cowpea (each year, 0.5 ha sorghum, 0.5 ha sole cowpea)	150	V2

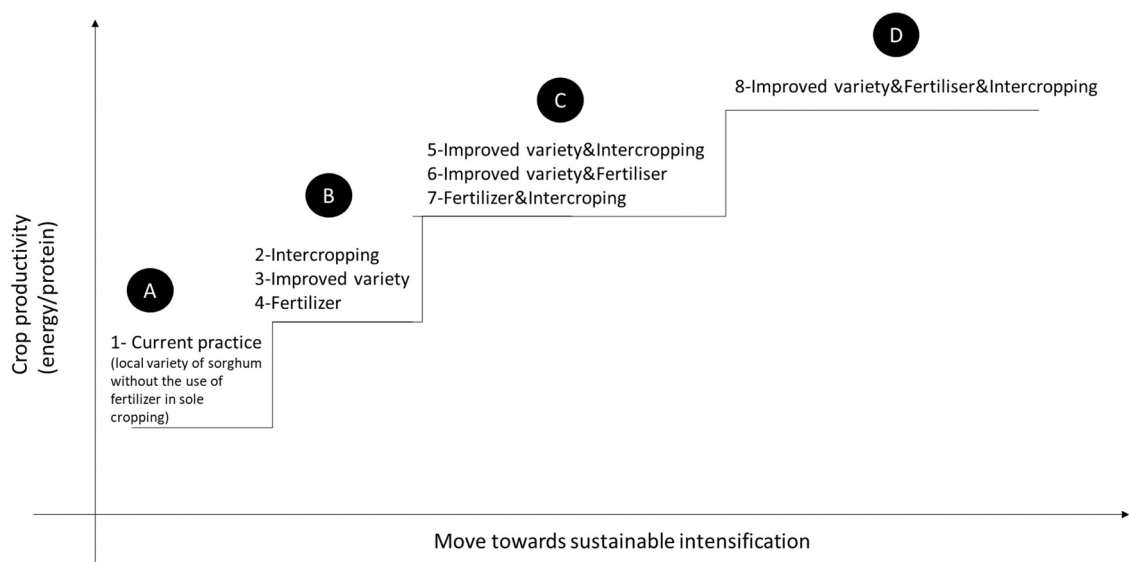


Fig. 1. Conceptual depiction of the move towards sustainable intensification of sorghum-based cropping systems in southern Mali. The current practice is the use of a local variety of sorghum without the use of fertilizer in sole cropping (step A, option 1). Strategy B involves the use of one innovative practice (options 2, 3 and 4), strategy C the use of three (options 5,6 and 7), and strategy D combines all of them (option 8). Adapted from Vanlauwe et al. (2014).

one would conclude that F1 gives less variable yields than F0. One would conclude the opposite using the IQR as a measure of variability – and we believe this aligns better with the idea of F1 being riskier, i.e. risk of unprofitable return related to greater investment.

For each year and option involving intercropping, we computed the pLER of sorghum and cowpea for five variables: cumulated radiation interception, cumulated plant transpiration, plant N uptake, above-ground biomass and grain yield. For each variable and each crop, the partial land equivalent ratio was defined as:

$$pLER = Y_i / Y_s \quad (1)$$

where Y_i is the value of the intercropping variable, and Y_s is that variable with sole cropping. LER was computed as the sum of the pLER of the two crops. In the last step, we compared all options involving intercropping to a counterpart where the legume would be integrated as a sole crop rather than an intercrop (see "bis" options in Table 1). To do so, the productivity (median and IQR for energy and protein) of one hectare

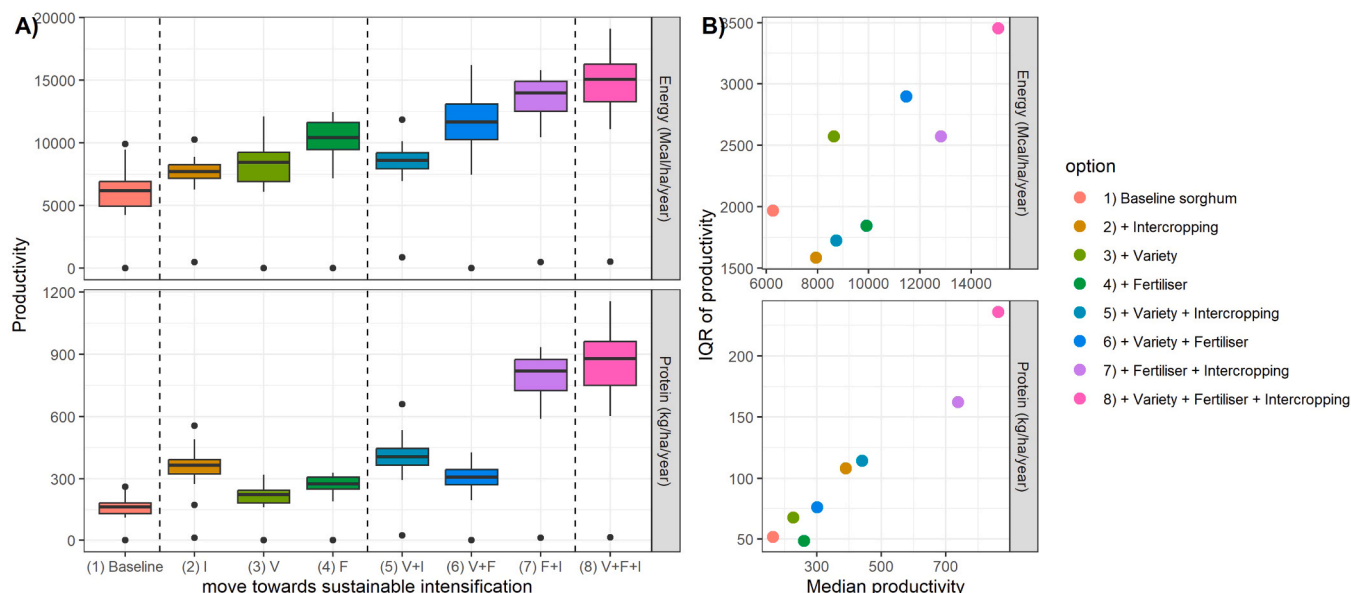


Fig. 2. A) Boxplots of simulated inter-annual productivity (for energy in $\text{Mcal ha}^{-1} \text{ year}^{-1}$ and protein in $\text{kg ha}^{-1} \text{ year}^{-1}$) of eight options towards sustainable intensification of sorghum-cropping systems. The vertical dotted lines separate the four steps towards sustainable intensification (see Fig. 1). B) Median and Inter Quartile Range (IQR) of productivity (for energy and protein) of these eight options. In A) the line in the box and the width of the box are the median and the interquartile range respectively. The whiskers extend from the edge of the box to the most extreme data point below $1.5 \times (Q3 - Q1)$ or above $Q3 + 1.5 \times (Q3 - Q1)$ where $Q1$ is the first quartile and $Q3$ the third quartile. Dots are outliers (i.e. data points below $Q1 - 1.5 \times (Q3 - Q1)$ or above $Q3 + 1.5 \times (Q3 - Q1)$). I=Intercropping, V=Improved sorghum variety, F=Fertilizer. Baseline sorghum is current farmers practice, i.e. the use of a local variety of sorghum without the use of fertilizer in sole cropping (step A, option 1). The reader is referred to the web version of this article for interpretation of references to colors. The yield failure (productivity $\sim 0 \text{ Mcal/ha/year}$) in A correspond to year 1984, a year with very little rainfall for the site (482 mm) and simulated crop failure due to drought stress for all crop management.

of intercropping was compared with the aggregated productivity of half a hectare of sorghum and half a hectare of cowpea. Because simulations were reset each year, the long-term benefits of the rotation (i.e. nutrient carry-over from one year to another) were not considered.

3. Results

3.1. Impact of incremental adoption of sustainable intensification options

The move toward sustainable intensification (i.e. intercropping with a legume, improved variety, and addition of mineral fertiliser, adopted alone, see strategy B in Fig. 1, or combination, see strategy C and D in Fig. 1) increased the productivity expressed in terms of energy and protein content per unit area (Fig. 2A). The combination of all options (variety, fertiliser, and intercropping) had the greatest median productivity in energy and protein. With regard to productivity in terms of protein, the options involving intercropping with cowpea (options 2, 5, 7 and 8, Fig. 2A) had greater median productivity compared with sole cropping options (options 1, 3, 4, 6, Fig. 2A).

An increase in median productivity (for both energy and protein) went hand in hand with an increase in inter-annual variability of this productivity, as expressed by the greater Inter quartile range (IQR) (Fig. 2B). This increase in inter-annual variability was linked to an increase in the sensitivity to variation in annual rainfall, as showed by an increase in the slope and the R^2 of the relation between productivity and annual rainfall when more options for intensification were adopted

(Figure S5). The best option concerning median productivity (option 8, combination of variety, fertiliser and intercropping) also had the greatest interquartile range (Fig. 2B) and the second highest slope and R^2 of the relation between productivity and annual rainfall (Figure S5). The options with intercropping and improved variety without fertiliser (options 2 and 5) were the only options that had a smaller IQR than the current farmers' practice (local sorghum without fertiliser) [Fig. 2B]. Intercropping helped reduce the inter-annual variability of productivity (when comparing with current farmers' practice, i.e. local sole sorghum without fertiliser), but only when fertiliser was not added. This was due to two things. Firstly, the simulated inter-annual variability of intercropped cowpea productivity was smaller than that of intercropped sorghum productivity (Fig. 3A). Secondly, without fertiliser, the contribution of the intercropped cowpea to the overall productivity (in terms of energy) of the intercropping was similar to that of intercropped sorghum. With fertiliser, this stable contribution of the cowpea became marginal, hence its role in stabilizing overall production across years (Fig. 3A). Simulated inter-annual variability of cowpea productivity was smaller than sorghum productivity because of smaller simulated water stress during grain filling for intercropped cowpea than sorghum (Fig. 3B). Lower water stress on cowpea than on sorghum was also observed on the sole crops (Figure S6) – it was not a specific feature of the intercropping.

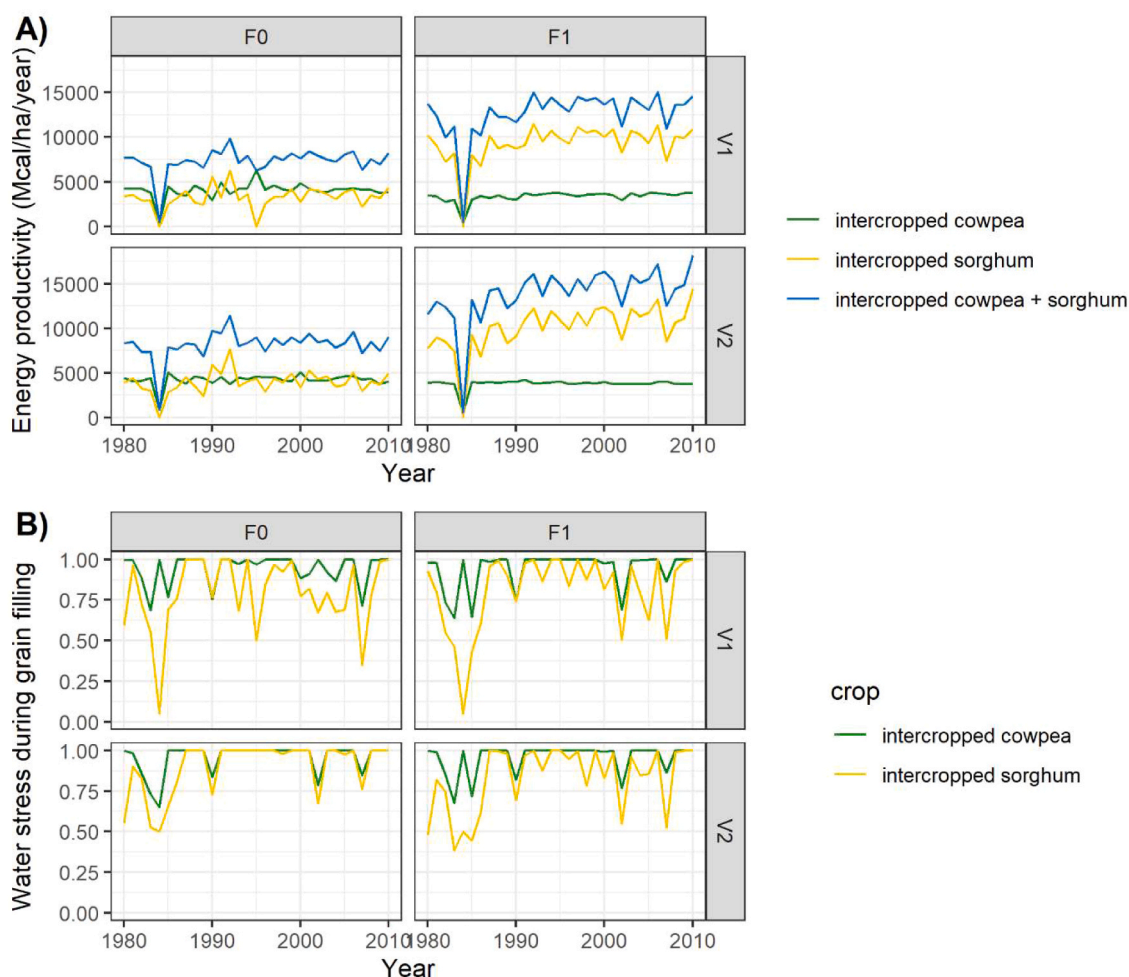


Fig. 3. A) Simulated inter-annual variations of productivity (in terms of energy) of intercropped sorghum and cowpea and B) Simulated water stress (1 no stress – 0 maximum stress) during reproductive phase of intercropped cowpea and intercropped sorghum, as a function of sorghum variety and fertilizer input. V1 = traditional sorghum variety, V2 = improved sorghum variety, F0 = 0 kgN/ha, F1 = 150 kgN/ha.

3.2. Integrating cowpea as sole or intercrop

Whatever the variety and the fertiliser level, one hectare of intercropping (options 2, 5, 7 and 8) was always more beneficial in terms of median productivity (for both energy and protein) than the cultivation of both sole crops, that is half a hectare of sole sorghum and half a hectare of sole cowpea (options 2bis, 5bis, 7bis and 8bis) (Figs. 4A, 4B). Yet, inter-annual variability of this productivity was similar (options 2 and 5 without fertiliser input) and greater (options 7 and 8, with fertiliser input) with intercropping than with sole crops (Figs. 4A, 4B). Interestingly, i) there is an *advantage* of cereal-legume intercropping compared to cultivating the two sole crops on the criteria of median productivity, and this advantage increases as more innovative options are employed (fertiliser, improved variety), and (ii) there is a *disadvantage* of cereal-legume intercropping compared to the two sole crops when it comes to the criteria of the IQR of productivity and this disadvantage also increases as more intensive management options are employed. In other words, the more intensive the cereal-legume combination, the higher the advantage of intercropping in median productivity, but the higher the advantage of the combination of sole crops in terms of low yield variability.

The greater productivity of intercropping compared with the combination of the two sole crops originated from a Land Equivalent Ratio for grain and biomass that was always above one for all the growing seasons of the virtual experiment, whatever the sorghum variety (Fig. 5). Simulated LER was greater with fertiliser (F1) than without (F0), thanks to a greater pLER for sorghum with fertiliser than without fertiliser and a similar pLER for cowpea with and without fertiliser: the competition of cowpea on sorghum was smaller with fertiliser than without fertiliser (Fig. 5 and Figure S8) whereas the competition of sorghum on cowpea was the same without and with fertiliser.

4. Discussion

4.1. Intercropping to reduce yield variability, but only at a low level of N

Our simulation outputs suggest that intercropping decreases yield variability of sorghum-based systems, but only without N fertilizer application. When fertilizer is applied, sorghum drives the productivity of the intercropping systems. The low amount of cowpea produced does not help to decrease the inter-annual variability in cropping system productivity. To the best of our knowledge, there are no similar modelling studies on the impact of cereal-legume intercropping on yield inter-annual variability for tropical climates. In their meta-analysis of 37 published studies, [Raseduzzaman and Jensen \(2017\)](#) investigated the impact of intercropping on yield stability. Nevertheless, most of the analysed studies were carried out in temperate climates, few in tropical climates in Africa (27% of the studies), even fewer on cereal-legume intercrops, and most of the latter type of studies did not include a comparison of varying N fertilizer inputs (i.e. N input was either 0 or the recommended dose). A useful exception is the study of [Waddington et al. \(2007\)](#) that investigated the productivity of substitutive maize-legume intercropping in a thirteen-year (1994–2006) experiment in sub-humid Zimbabwe. The authors did not analyze yield variability in particular. Our analysis of their published data indicates, in line with the findings of this modelling study, that fertilizer input drastically increased the inter-annual variability of maize yield, and that intercropping with cowpea only marginally contributed to reduce this inter-annual variability (Figure S7). Exploring with modelling the impact on intercropping performance of a wider range of N inputs (i.e. intermediate amount in the range 40–150 kgN/ha) would help identify the input rate that maximizes the benefits of intercropping in terms of increasing and stabilizing yield.

4.2. Contrasted sensitivities to water stress of sorghum and cowpea

At low level of N, intercropping with cowpea contributed to stabilising cropping system productivity due to a substantial contribution of

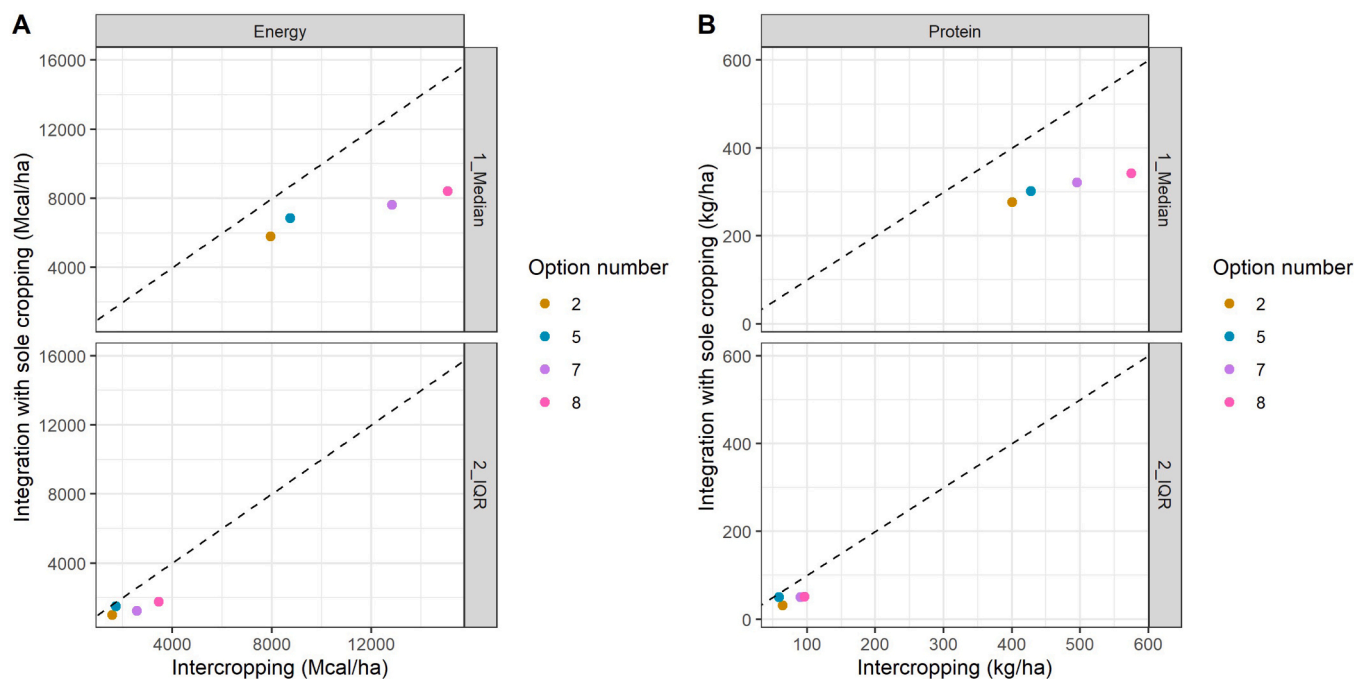


Fig. 4. A) Productivity (in terms of energy) of legume integration with sole cropping (y-axis) compared with productivity of intercropping (x-axis) for four options of cereal-legume integration. B) Productivity (in terms of protein) of legume integration with sole cropping (y-axis) compared with productivity of intercropping (x-axis) for the same four options. Option 2 = local sorghum variety, option 5 = improved sorghum variety, option 7 = local sorghum variety and mineral fertilizer, option 8 = improved sorghum variety and fertilizer (Table 1). IQR = Inter-quartile range.

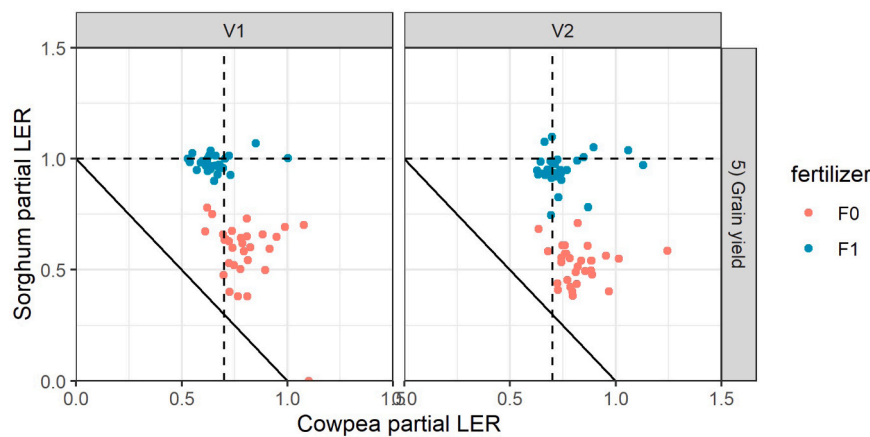


Fig. 5. Sorghum partial LER and cowpea partial LER for cumulated intercepted radiation (throughout crop cycle), cumulated transpiration, N uptake, aboveground biomass (AGB) and grain yield as simulated by the Stics model for a 30 years historical weather series (1980–2010). V1 = traditional sorghum variety, V2 = improved sorghum variety, F0 = 0 kgN/ha, F1 = 150 kgN/ha. Each dot is one simulation. The vertical dotted lines are the pLER value of 1 that corresponds to the relative density of cowpea in the intercrop (i.e. the same density as the sole crop, as a fully additive design was considered).

the cowpea to total productivity and stable production owing to lower water stress compared with sorghum. Our calibration of the impact of water stress on sole cowpea was based on one single simulation unit in a year with good rainfall (Traoré et al., 2022), so this finding of lower impact of water stress on cowpea compared with sorghum should be interpreted with care. More observations of cowpea growth in drier years and refinement of model calibration are required to confirm this finding. Our simulation outcome of greater sensitivity of sorghum to water stress compared with cowpea contrasts with the findings of the meta-analysis of Daryanto et al. (2017). The authors showed that cereals were more resistant to drought stress than legumes on average. They found that the yield of cowpea decreased by 43% ($n = 55$) on average, for an average water reduction of 38%, while the yield of sorghum decreased by 27% only ($n = 170$), for an even greater water reduction (55% on average). The authors of the synthesis attributed this advantage to the deeper rooting systems of the cereal compared to that of the legume. However, research in West and East Africa points to deeper rooting systems of the legume compared to cereal: e.g., the root front extended to 150 cm for groundnut in Senegal and to only 120 cm for sorghum (Chopart, 2015). Pigeon pea roots were found up to two meters in Northern Tanzania and only up to 60 cm for maize (Mugi-Ngenga et al., 2023). Then, in line with our simulation outcome, Raseduzzaman and Jensen (2017) found with meta-analysis that the yield variability of legumes (expressed with the coefficient of variation) was smaller than that of the cereal in tropical regions. Given this lack of consensus in the literature, more measurements (leaf area index, soil moisture, and maximum rooting depth for irrigated vs rainfed cowpea) will be critical to confirm the simulation output of this study. In addition, soil type and soil depth vary spatially in farmers context (Falconnier et al., 2016). Exploring how this variability impacts water stress of the companion crops will be critical for a better understanding of the local relevance of intercropping.

4.3. Sole vs intercrop: trading productivity for less variability?

Additive intercropping of sorghum and cowpea provided greater median productivity for energy and protein than a land allocation strategy based on an equal share of the sole cereal and the sole legume. This advantage grew bigger as additional sustainable intensification options (improved sorghum variety, mineral fertilizer) were implemented. However, greater productivity of the intercropping came with lower yield stability compared with the integration of legume as a sole crop. This could be attributed to greater intra-specific competition for resources in the intercrop systems than in the sole crop systems (e.g.

Chimonyo et al., 2016). Intercropping sorghum with the improved variety and fertilizer input generated a median relative gain in energy of 149% (454% when considering protein) compared with the sole cropping of local sorghum, but the gain could be as low as 28%, and 169% when considering protein, in drier years of our historical series. A detailed partial gross margin analysis, including the extra cost of the improved sorghum seed, cowpea seed, and mineral fertilizer, and possibly extra labour demand, is required to determine the probability for farmers to break even and the risk associated with sustainable intensification using improved sorghum, fertilizer, and intercropping. Based on data from on-farm trials in multiple locations and years, Falconnier et al. (2017) calculated that the probability of profit using improved sorghum variety and mineral fertilizer was only around 50% for farmers in southern Mali. In their long-term experiment, Waddington et al. (2007) found that the economic return of sole fertilized maize outperformed the legume intercropping options in nine of the 12 years of the experiment.

Whether farmers will prefer intercropping over sole cropping of the cereal and the legumes will ultimately depend on the economic risk of the two strategies. Allocating a portion of the land to the sole legume means that there could be rotational benefits for the following cereal that were not considered in this study. The yield of the sole legume is usually greater than the yield of the intercropped legume so that the benefits of the decomposition of the legume residues on the productivity of the subsequent cereal are usually greater with rotation than with intercropping (Thierfelder et al., 2012). Intercropping and rotation with legumes also come with several other benefits not included in this study, like pest, disease and weed regulation (Ripoche et al., 2021). Rotations are useful to prevent soil-born pests that could result from intercropping the same crops every year in the same plot (Ripoche et al., 2021). More studies aiming at comparing rotation and intercropping would help understand whether temporal integration of legumes (pre-crop effect through rotation) has a greater advantage than spatial integration of legumes (intercropping) in cropping systems (see the useful example of Gwenambira-Mwika et al., 2021).

Careful gross margin and risk analysis that accounts for farmers objectives and the economic environment of the farm must be undertaken to understand the opportunities for farmers to adopt the typical cropping options of our study. Nevertheless, our results suggest that legume integration cannot substantially help cushion farmers against the risk associated with sustainable intensification. This raises the question of other mechanisms to incentivize farmers. Index-based insurance is a promising opportunity, but only when risks are very high (Ricombe et al., 2017). Legumes deliver several environmental benefits

beyond farmer income, e.g. a decrease in mineral nitrogen required (and thus the associated nitrous oxide emissions) to increase cereal yield (see e.g. Ranaivoson et al., 2022). For this reason, payment for ecosystem services could also be an entry point (e.g. Jourdain et al., 2014).

5. Conclusion

Integration of legumes is key for sustainable intensification of cereals in cropping systems of SSA. Our modelling study on sorghum and cowpea as a typical case shows that intercropping the cereal with the legume, combined with mineral fertilisation and using an improved cereal variety, increases median productivity in terms of energy and protein. The impact of the improved cereal variety was relatively smaller than the impact of the two other options. The often-claimed benefit of intercropping on reducing the inter-annual variability of production does not hold when the three options are combined. Intercropping only stabilised production at low level of N input, with only a slight increase in median productivity. Under greater N inputs on the cereal, our simulation suggested that having the two crops grown separately provided more stable energy and protein yield than intercropping them. This gain in the stability of sole crops under greater nutrient supply seemed to come at the cost of smaller productivity gains on average, and this is obviously due to the absence of facilitations between the two sole crops grown separately, unlike simulated in intercropping. Possibly, the risk of competition for water increased with fertilised intercropping more than under its low nutrient input variant.

This modelling outcome is supported by the rare long-term experiment reported on cereal-legume intercropping but needs to be confirmed with further calibration of water stress impact on both the cereal and legume growth. Ultimately, the choices of farmers for one option or another will depend on non-biophysical elements of their local context that were not in the scope of this study, such as the profitability of these options and possible policy incentives that could cushion farmers against the risk associated with their adoption.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data Availability

Data will be made available on request.

Acknowledgements

The Agriculture and Climate Risk Management program: Tools and Research in Africa (FSP-AGRICORA project, MEAE/IRD, France) funded the fieldwork of this study. The first author acknowledges the support of "Service de Coopération et d'Action Culturelle" of the French embassy in Mali (SCAC-Mali).

Appendix A. Supporting information

Supplementary data associated with this article can be found in the online version at [doi:10.1016/j.fcr.2023.109180](https://doi.org/10.1016/j.fcr.2023.109180).

References

- Adam, M., MacCarthy, D.S., Traoré, P.C.S., Nenkam, A., Freduah, B.S., Ly, M., Adiku, S. G.K., 2020. Which is more important to sorghum production systems in the Sudano-Sahelian zone of West Africa: climate change or improved management practices? *Agric. Syst.* 185, 102920 <https://doi.org/10.1016/j.agsy.2020.102920>.
- Affholder, F., 1997. Empirically modelling the interaction between intensification and climatic risk in semi-arid regions. *Field Crops Res.* 52, 79–93. [https://doi.org/10.1016/S0378-4290\(96\)03453-3](https://doi.org/10.1016/S0378-4290(96)03453-3).
- Amouzou, K.A., Lamers, J.P.A., Naab, J.B., Borgemeister, C., Vlek, P.L.G., Becker, M., 2019. Climate change impact on water- and nitrogen-use efficiencies and yields of maize and sorghum in the northern Benin dry savanna, West Africa. *Field Crops Res.* 235, 104–117. <https://doi.org/10.1016/j.fcr.2019.02.021>.
- Baldé, A.B., Scopel, E., Affholder, F., Corbeels, M., Da Silva, F.A.M., Xavier, J.H.V., Wery, J., 2011. Agronomic performance of no-tillage relay intercropping with maize under smallholder conditions in Central Brazil. *Field Crops Research*, This Issue Includes a Special Issue Section on: The Use of Field Crop Knowledge in Integrative Inter-Scale Systems Approaches: The Plant, the Field and the Property 124, 240–251. <https://doi.org/10.1016/j.fcr.2011.06.017>.
- Bielders, C.L., Gérard, B., 2015. Millet response to microdose fertilization in south-western Niger: effect of antecedent fertility management and environmental factors. *Field Crops Res.* 171, 165–175. <https://doi.org/10.1016/j.fcr.2014.10.008>.
- Bonilla Cedrez, C., Chamberlin, J., Hijmans, R.J., 2021. Fertilizer and grain prices constrain food production in sub-Saharan Africa. *Nat. Food* 2, 766–772. <https://doi.org/10.1038/s43016-021-00370-1>.
- Brisson, N., Bussière, F., Ozier-Lafontaine, H., Tournéize, R., Sinoquet, H., 2004. Adaptation of the crop model STICS to intercropping. Theoretical basis and parameterisation. *Agronomie* 24, 409–421. <https://doi.org/10.1051/agro:2004031>.
- Chimonyo, V.G.P., Modi, A.T., Mabhaudhi, T., 2016. Water use and productivity of a sorghum–cowpea–bottle gourd intercrop system. *Agric. Water Manag.* 165, 82–96. <https://doi.org/10.1016/j.agwat.2015.11.014>.
- Chimonyo, V.G.P., Snapp, S.S., Chikowo, R., 2019. Grain legumes increase yield stability in maize based cropping systems. *Crop Sci.* 59, 1222–1235. <https://doi.org/10.2135/cropsci2018.09.0532>.
- Chopart, J.L., 2015. Root fronts of pearl millet (*Pennisetum glaucum*), sorghum (*Sorghum bicolor*) and groundnut (*Arachis hypogaea*) in a deep soil in Senegal. ISRR-9 Roots Down Under. Canberra: International Society of Root Research, Résumé, 1 p. Symposium of the International Society of Root Research. 9, Canberra, Australie, 6 Octobre 2015/9 Octobre 2015. <http://www.isrr9.com.au/index.asp?IntCatId=14>.
- Couchene, E., Buis, S., Launay, M., Constantin, J., Mary, B., García de Cortázar-Atauri, I., Ripoche, D., Beaudoin, N., Ruget, F., Andrianarisoa, K.S., Le Bas, C., Justes, E., Léonard, J., 2015. Accuracy, robustness and behavior of the STICS soil–crop model for plant, water and nitrogen outputs: Evaluation over a wide range of agro-environmental conditions in France. *Environ Model Softw* 64, 177–190. <https://doi.org/10.1016/j.envsoft.2014.11.024>.
- Daryanto, S., Wang, L., Jacinthe, P.-A., 2017. Global synthesis of drought effects on cereal, legume, tuber and root crops production: a review. *Agric. Water Manag.* 179, 18–33. <https://doi.org/10.1016/j.agwat.2016.04.022>.
- Falconnier, G.N., 2016. Trajectories of agricultural change in southern Mali (phd). Wageningen University, Wageningen.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Giller, K.E., 2016. Unravelling the causes of variability in crop yields and treatment responses for better tailoring of options for sustainable intensification in southern Mali. *Field Crops Res.* 187, 113–126. <https://doi.org/10.1016/j.fcr.2015.12.015>.
- Falconnier, G.N., Descheemaeker, K., Traore, B., Bayoko, A., Giller, K.E., 2018. Agricultural intensification and policy interventions: exploring plausible futures for smallholder farmers in Southern Mali. *Land Use Policy* 70, 623–634. <https://doi.org/10.1016/j.landusepol.2017.10.044>.
- Falconnier, G.N., Descheemaeker, K., Van Mourik, T.A., Adam, M., Sogoba, B., Giller, K. E., 2017. Co-learning cycles to support the design of innovative farm systems in southern Mali. *Eur. J. Agron.* 89, 61–74. <https://doi.org/10.1016/j.eja.2017.06.008>.
- Falconnier, G.N., Journet, E.-P., Bedoussac, L., Vermue, A., Chlébowski, F., Beaudoin, N., Justes, E., 2019. Calibration and evaluation of the STICS soil-crop model for faba bean to explain variability in yield and N₂ fixation. *Eur. J. Agron.* 104, 63–77. <https://doi.org/10.1016/j.eja.2019.01.001>.
- Falconnier, G.N., Cardinael, R., Corbeels, M., Baudron, F., Chivenge, P., Couédel, A., Ripoche, A., Affholder, F., Naudin, K., Benaillon, E., Rusinamhodzi, L., Leroux, L., Vanlauwe, B., Giller, K.E., 2023a. The input reduction principle of agroecology is wrong when it comes to mineral fertilizer use in sub-Saharan Africa, 00307270231199795 Outlook Agric. <https://doi.org/10.1177/00307270231199795>.
- Falconnier, G.N., Leroux, L., Beillouin, D., Corbeels, M., Hijmans, R.J., Bonilla-Cedrez, C., van Wijk, M., Descheemaeker, K., Zingore, S., Affholder, F., Lopez-Ridaura, S., Malézieux, E., Makowski, D., Rurinda, J., van Ittersum, M.K., Vanlauwe, B., Giller, K. E., Lammoglia, S.-K., Waha, K., 2023b. Increased mineral fertilizer use on maize can improve both household food security and regional food production in East Africa. *Agric. Syst.* 205, 103588 <https://doi.org/10.1016/j.agsy.2022.103588>.
- Falconnier, G.N., Corbeels, M., Boote, K.J., Affholder, F., Adam, M., MacCarthy, D.S., Ruane, A.C., Nendel, C., Whitbread, A.M., Justes, E., Ahuja, L.R., Akinseye, F.M., Alou, I.N., Amouzou, K.A., Anapalli, S.S., Baron, C., Basso, B., Baudron, F., Bertuzzi, P., Challinor, A.J., Chen, Y., Deryng, D., Elsayed, M.L., Faye, B., Gaiser, T., Galdos, M., Gayler, S., Gerardeaux, E., Giner, M., Grant, B., Hoogenboom, G., Ibrahim, E.S., Kamali, B., Kersebaum, K.C., Kim, S.-H., van der Laan, M., Leroux, L., Lizaso, J.I., Maestrini, B., Meier, E.A., Mequanint, F., Ndoli, A., Porter, C.H., Priesack, E., Ripoche, D., Sida, T.S., Singh, U., Smith, W.N., Srivastava, A., Sinha, S., Tao, F., Thorburn, P.J., Timlin, D., Traore, B., Twine, T., Webber, H., 2020. Modelling climate change impacts on maize yields under low nitrogen input conditions in sub-Saharan Africa. *Glob. Change Biol.* 26, 5942–5964. <https://doi.org/10.1111/gcb.15261>.
- FAO, IFAD, UNICEF, WFP, WHO, 2022. The State of Food Security and Nutrition in the World 2022: Repurposing food and agricultural policies to make healthy diets more affordable, The State of Food Security and Nutrition in the World (SOFI). FAO, IFAD, UNICEF, WFP, WHO, Rome, Italy. <https://doi.org/10.4060/cc0639en>.

- Folberth, C., Yang, H., Gaiser, T., Abbaspour, K.C., Schulin, R., 2013. Modeling maize yield responses to improvement in nutrient, water and cultivar inputs in sub-Saharan Africa. *Agric. Syst.* 119, 22–34. <https://doi.org/10.1016/j.agsy.2013.04.002>.
- Frankin, S., Roychowdhury, R., Nashif, K., Abbo, S., Bonfil, D.J., Ben-David, R., 2021. In-field comparative study of landraces vs. modern wheat genotypes under a mediterranean climate. *Plants* 10, 2612. <https://doi.org/10.3390/plants10122612>.
- Ganeme, A., Douzet, J.-M., Traoré, S., Dusserre, J., Kaboré, R., Tirogo, H., Nabaloum, O., Ouedraogo, N.W.-Z.S., Adam, M., 2021. L'association sorgho/niébé au poquet, une pratique traditionnelle en zone soudano-sahélienne à faible rendement: état des lieux et pistes d'amélioration. *International Journal of Innovation and Applied Studies*. Gwembira-Mwika, C.P., Snapp, S.S., Chikowo, R., 2021. Broadening farmer options through legume rotational and intercrop diversity in maize-based cropping systems of central Malawi. *Field Crops Res.* 270, 108225 <https://doi.org/10.1016/j.fcr.2021.108225>.
- Huet, E.K., Adam, M., Traore, B., Giller, K.E., Descheemaeker, K., 2022. Coping with cereal production risks due to the vagaries of weather, labour shortages and input markets through management in southern Mali. *Eur. J. Agron.* 140, 126587 <https://doi.org/10.1016/j.eja.2022.126587>.
- Jayne, T.S., Mason, N.M., Burke, W.J., Ariga, J., 2018. Review: taking stock of Africa's second-generation agricultural input subsidy programs. *Food Policy* 75, 1–14. <https://doi.org/10.1016/j.foodpol.2018.01.003>.
- Jourdain, D., Lairez, J., Striffler, B., Affholder, F., 2020. Farmers' preference for cropping systems and the development of sustainable intensification: a choice experiment approach. *Rev. Agric. Food Environ. Stud.* 101, 417–437. <https://doi.org/10.1007/s41130-020-00100-4>.
- Jourdain, D., Boere, E., van den Berg, M., Dang, Q.D., Cu, T.P., Affholder, F., Pandey, S., 2014. Water for forests to restore environmental services and alleviate poverty in Vietnam: a farm modeling approach to analyze alternative PES programs. *Land Use Policy* 41, 423–437. <https://doi.org/10.1016/j.landusepol.2014.06.024>.
- Kante, M., Rattunde, F., Nèbié, B., Sissoko, I., Diallo, B., Diallo, A., Touré, A., Weltzien, E., Haussmann, B.I.G., Leiser, W.L., 2019. Sorghum hybrids for low-input farming systems in west Africa: quantitative genetic parameters to guide hybrid breeding. *Crop Sci.* 59, 2544–2561. <https://doi.org/10.2135/cropsci2019.03.0172>.
- Loon, van, Hijbeek, M.P., Berge, R., ten, H.F.M., Sy, V.D., Broeke, G.A. ten, Solomon, Ittersum, D., van, M.K., 2019. Impacts of intensifying or expanding cereal cropping in sub-Saharan Africa on greenhouse gas emissions and food security. *Glob. Change Biol.* 25, 3720–3730. <https://doi.org/10.1111/gcb.14783>.
- Mugi-Ngenga, E., Bastiaans, L., Anten, N.P.R., Zingore, S., Baijuka, F., Giller, K.E., 2023. The role of inter-specific competition for water in maize-legume intercropping systems in northern Tanzania. *Agric. Syst.* 207, 103619 <https://doi.org/10.1016/j.agsy.2023.103619>.
- Mupangwa, W., Nyagumbo, I., Liben, F., Chipindu, L., Craufurd, P., Mkuhlani, S., 2021. Maize yields from rotation and intercropping systems with different legumes under conservation agriculture in contrasting agro-ecologies. *Agric., Ecosyst. Environ.* 306, 107170 <https://doi.org/10.1016/j.agee.2020.107170>.
- Namatshve, T., Cardinael, R., Corbeels, M., Chikowo, R., 2020. Productivity and biological N₂-fixation in cereal-cowpea intercropping systems in sub-Saharan Africa. A review. *Agron. Sustain. Dev.* <https://doi.org/10.1007/s13593-020-00629-0>.
- Namatshve, T., Chikowo, R., Corbeels, M., Mouquet-Rivier, C., Icard-Vernière, C., Cardinael, R., 2021. Maize-cowpea intercropping as an ecological intensification option for low input systems in sub-humid Zimbabwe: productivity, biological N₂-fixation and grain mineral content. *Field Crops Res.* 263, 108052 <https://doi.org/10.1016/j.fcr.2020.108052>.
- Njoroge, S., Schut, A.G.T., Giller, K.E., Zingore, S., 2017. Strong spatial-temporal patterns in maize yield response to nutrient additions in African smallholder farms. *Field Crops Res.* 214, 321–330. <https://doi.org/10.1016/j.fcr.2017.09.026>.
- Peter, G., Runge-Metzger, A., 1994. Monocropping, intercropping or crop rotation? An economic case study from the West African Guinea savannah with special reference to risk. *Agric. Syst.* 45, 123–143. [https://doi.org/10.1016/0308-521X\(94\)90174-E](https://doi.org/10.1016/0308-521X(94)90174-E).
- Pieri, C., 1989. Fertilité des terres de savanes. Bilan de trente ans de recherche et de développement agricoles au Sud du Sahara. Montpellier: CIRAD-IRAT, 452 p. ISBN 2-87614-024-1.
- Ranaivosoa, L., Falconnier, G.N., Affholder, F., Leroux, L., Autray, P., Muller, B., Auzoux, S., Ripoche, A., 2022. Can green manure contribute to sustainable intensification of rainfed rice production in Madagascar? *Field Crops Res.* 289, 108711 <https://doi.org/10.1016/j.fcr.2022.108711>.
- Raseduzzaman, Md, Jensen, E.S., 2017. Does intercropping enhance yield stability in arable crop production? A meta-analysis. *Eur. J. Agron.* 91, 25–33. <https://doi.org/10.1016/j.eja.2017.09.009>.
- Ricome, A., Affholder, F., Gérard, F., Muller, B., Poeydebat, C., Quirion, P., Sall, M., 2017. Are subsidies to weather-index insurance the best use of public funds? A bio-economic farm model applied to the Senegalese groundnut basin. *Agric. Syst.* 156, 149–176. <https://doi.org/10.1016/j.agsy.2017.05.015>.
- Ripoche, A., Crétenet, M., Corbeels, M., Affholder, F., Naudin, K., Sissoko, F., Douzet, J.-M., Titttonell, P., 2015. Cotton as an entry point for soil fertility maintenance and food crop productivity in savannah agroecosystems: Evidence from a long-term experiment in southern Mali. *Field Crops Res.* 177, 37–48. <https://doi.org/10.1016/j.fcr.2015.02.013>.
- Ripoche, A., Autray, P., Rabary, B., Randriamanantsoa, R., Blanchart, E., Trap, J., Sauvadet, M., Becquer, T., Letourmy, P., 2021. Increasing plant diversity promotes ecosystem functions in rainfed rice based short rotations in Malagasy highlands. *Agric., Ecosyst. Environ.* 320, 107576 <https://doi.org/10.1016/j.agee.2021.107576>.
- Sheahan, M., Barrett, C.B., 2017. Ten striking facts about agricultural input use in Sub-Saharan Africa. *Food Policy, Agric. Afr. – Tell. Myths Facts* 67, 12–25. <https://doi.org/10.1016/j.foodpol.2016.09.010>.
- Shuttleworth, W.J., Wallace, J.S., 1985. Evaporation from sparse crops—an energy combination theory. *Q. J. R. Meteorol. Soc.* 111, 839–855. <https://doi.org/10.1002/qj.49711146910>.
- ten Berge, H.F.M., Hijbeek, R., van Loon, M.P., Rurinda, J., Tesfaye, K., Zingore, S., Craufurd, P., van Heerwaarden, J., Brentrup, F., Schröder, J.J., Boogaard, H.L., de Groot, H.L.E., van Ittersum, M.K., 2019. Maize crop nutrient input requirements for food security in sub-Saharan Africa. *Glob. Food Secur.* 23, 9–21. <https://doi.org/10.1016/j.gfs.2019.02.001>.
- Thierfelder, C., Cheesman, S., Rusinamhodzi, L., 2012. A comparative analysis of conservation agriculture systems: Benefits and challenges of rotations and intercropping in Zimbabwe. *Field Crops Res.* 137, 237–250. <https://doi.org/10.1016/j.fcr.2012.08.017>.
- Traore, B., Corbeels, M., van Wijk, M.T., Rufino, M.C., Giller, K.E., 2013a. Effects of climate variability and climate change on crop production in southern Mali. *Eur. J. Agron.* 49, 115–125. <https://doi.org/10.1016/j.eja.2013.04.004>.
- Traore, B., Corbeels, M., van Wijk, M.T., Rufino, M.C., Giller, K.E., 2013b. Effects of climate variability and climate change on crop production in southern Mali. *Eur. J. Agron.* 49, 115–125. <https://doi.org/10.1016/j.eja.2013.04.004>.
- Traoré, A., Falconnier, G.N., Ba, A., Sissoko, F., Sultan, B., Affholder, F., 2022. Modeling sorghum-cowpea intercropping for a site in the savannah zone of Mali: Strengths and weaknesses of the Stics model. *Field Crops Res.* 285, 108581 <https://doi.org/10.1016/j.fcr.2022.108581>.
- USDA, 2023a. FoodData Central Search Results. (<https://fdc.nal.usda.gov/fdc-app.html#/food-details/169716/nutrients>).
- USDA, 2023b. FoodData Central Search Results. (<https://fdc.nal.usda.gov/fdc-app.html#/food-details/173758/nutrients>).
- van Ittersum, M.K., van Bussel, L.G.J., Wolf, J., Grassini, P., van Wart, J., Guilpart, N., Claessens, L., de Groot, H., Wiebe, K., Mason-D'Croz, D., Yang, H., Boogaard, H., van Oort, P.A.J., van Loon, M.P., Saito, K., Adimo, O., Adjei-Nsiah, S., Agali, A., Bala, A., Chikowo, R., Kaizzi, K., Kouressy, M., Makoi, J.H.J.R., Ouattara, K., Tesfaye, K., Cassman, K.G., 2016. Can sub-Saharan Africa feed itself? *Proc. Natl. Acad. Sci. USA* 113, 14964–14969. <https://doi.org/10.1073/pnas.1610359113>.
- Vanlauwe, B., Coe, R., Giller, K.E., 2019. Beyond averages: new approaches to understand heterogeneity and risk of technology success or failure in smallholder farming. *Exp. Agric.* 55, 84–106. <https://doi.org/10.1017/S0014479716000193>.
- Vanlauwe, B., Kihara, J., Chivenge, P., Pypers, P., Coe, R., Six, J., 2011. Agronomic use efficiency of N fertilizer in maize-based systems in sub-Saharan Africa within the context of integrated soil fertility management. *Plant Soil* 339, 35–50. <https://doi.org/10.1007/s11104-010-0462-7>.
- Vanlauwe, B., Descheemaeker, K., Giller, K.E., Huising, J., Merckx, R., Nziguheba, G., Wendt, J., Zingore, S., 2015. Integrated soil fertility management in sub-Saharan Africa: unravelling local adaptation. *SOIL* 1, 491–508. <https://doi.org/10.5194/soil-1-491-2015>.
- Vanlauwe, B., Coyne, D., Gockowski, J., Hauser, S., Huising, J., Masso, C., Nziguheba, G., Schut, M., Van Asten, P., 2014. Sustainable intensification and the African smallholder farmer. *Curr. Opin. Environ. Sustain.* 8, 15–22. <https://doi.org/10.1016/j.cosust.2014.06.001>.
- Waddington, S.R., Mekuria, M., Siziba, S., Karigwindi, J., 2007. Long-term yield sustainability and financial returns from grain legume–maize intercrops on a sandy soil in subhumid north central zimbabwe. *Exp. Agric.* 43, 489–503. <https://doi.org/10.1017/S0014479707005303>.
- Willmott, C.J., Ackleson, S.G., Davis, R.E., Feddema, J.J., Klink, K.M., Legates, D.R., O'Donnell, J., Rowe, C.M., 1985. Statistics for the evaluation and comparison of models. *J. Geophys. Res.* 90, 8995. <https://doi.org/10.1029/JC090iC05p08995>.