September 16, 2014 — September 15, 2020

PHASE 1 FINAL REPORT

Innovation Lab for Collaborative Research on Sustainable Intensification

Transforming farming systems for smallholders

Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification

Five-Year Final Report

September 16, 2014 – September 15, 2019

This five-year final report is made possible by the generous support of the American people through the United States Agency of International Development (USAID). The contents are the responsibility of Kansas State University and do not necessarily reflect the views of USAID or the United States Government.

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Front cover photo:

A woman in Bobo-Dioulasso tests a mechanization tool during a gender sensitivity technology assessment training (Burkina Faso).
Photo credit: Maria Jones

Back cover photos (Top; bottom – left to right):
Woman in her field (Tanzania).
Photo credit: Jovin Lwehabura

Farmer to farmer rice reaper training in Khulna (Bangladesh).
Photo credit: Krishna Jagadish

A graduate student showcases a healthy tomato crop of grafted tomatoes in Phnom Penh (Cambodia).
Photo credit: Rick Bates

Demonstration of machine transplanting in coastal polders (Bangladesh).
Photo credit: Krishna Jagadish

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SI INNOVATION LAB

IN FIVE YEARS

collaborated with over **80 national & international organizations & 13 U.S. universities**

supported ***115 scholars***

Short-term trainings offered to **13,456** individuals across **268** unique trainings

5,020 women | **37 %** average

assisted in funding for **115 individuals** — **45 women** for a total of **39 percent**

SIIL researchers produced **505 publications,** presentations, dissertations and other documents over the past five years

EXECUTIVE SUMMARY

This report represents the activity highlights from the first phase of the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) over the past five years since its inception. All projects completed four years of active research and data collection in SIIL's focus countries (Bangladesh, Burkina Faso, Cambodia, Ethiopia, Malawi, Senegal, and Tanzania) and all activities were aligned with the vision of SIIL and its main objectives.

There are a variety of representative activities, accomplishments and lessons learned which are detailed in this Five-Year Report. This executive summary provides highlights of a few key activities related to the SIIL's mission and goals during their first phase, as well as some statistics tied to training and capacity-building. Project teams identified promising innovations from their research using a systems approach, and by actively collaborating with our strategic partners to leverage investments, and communicating our successes through our multiple knowledge management platforms, they have been key to successful implementation that will ensure greater impact and return on investments during the next phase. Through the first five years of the SIIL program, they collaborated with over 80 national and international organizations (including 8 CGIAR and 13 US universities), and supported 115 scholars to work towards common themes of increasing sustainable agriculture productivity, enhancing the resilience of cropping systems, and supporting nutritional outcomes.

Each of the projects have gathered important information and seen major achievements. The Geospatial and Farming Systems Research Consortium supported the quantification of the SIIL's Sustainable Intensification Assessment Framework using RHoMIS data from SIIL's Subawards in Senegal and Burkina Faso, as well as the AfricaRISING Ethiopia project.

The Appropriate Scale Mechanization Consortium (ASMC) developed an Agricultural Mechanization degree program within the Institute of Rural Development at Polytechnic University of Bobo-Dioulasso in collaboration with the Institute of Technology in Burkina Faso. The ASMC also hosted numerous trainings focused on private sector enterprises to improve service business related agricultural mechanization techniques. The Bangladesh project focused on high yielding and stress tolerant rice varieties, improve productivity of rice and fish cultivation, and introduce high value rabi crops to increase farm income and improve household nutrition. Burkina Faso continued to focus on demonstrating benefits of grain and biomass yields with dual-purpose sorghum and cowpea.

The WAgN Cambodia project continued to empower women and improve nutrition by promoting women's participation in the value chains for horticultural crops and rice produced via sustainable intensification (SI) practices. Ethiopia found that multiple maize crops cultivated after irrigated and fertilized vegetables or fodder increased maize yield substantially as compared to baseline conditions due soil fertility improvement from residual nutrients from dry season cropping. The Senegal team promoted sustainably intensified production and management practices of dual-purpose millet and leguminous crops (cowpea and groundnut) with small ruminant livestock (goats and sheep) integration. The Malawi team completed their project and built geospatial tools to integrate available data sets and mapped much of the country. Lastly, the Tanzania team evaluated bidirectional learning and extension approaches to promote SI technologies among researchers, extension, agrodealers, NGOs, and farmers and analyzed household surveys.

Other highlights include: a) finalization of the Research Output Dissemination study that focused on evaluating the path from development to end-user for selected innovations produced by the Feed the

Future Innovation Labs, b) launch and implementation of the SOILS consortium with the IFDC and the Policy Research Consortium with Rutgers University, c) creating an online presence to continue to promote the SI Assessment Framework, and, d) development of a pilot Innovation, Research, Extension and Advisory Coordination Hub (iREACH) in West Africa in collaboration with CORAF and USAID Missions.

SIIL is committed to human and institutional capacity building as evidenced by the number of short-term trainings offered to 13,456 individuals (5,020 women, 37% average overall) across 268 unique trainings. The SIIL is also committed to the support of long-term undergraduate and graduate degree training, helping to fund 115 individuals (45 women, 39%). In addition, the SIIL researchers produced 505 publications, presentations, dissertations, and other documents over the past five years. SIIL country coordinators continued to provide support to partners on the implementation and coordination of research, capacity building activities, communication and support of ongoing research.

PROGRAM PARTNERS

UNITED STATES

ADM Institute for the Prevention of Postharvest Loss
American Soybean Association (ASA)
Feed the Future Innovation Lab for Horticulture
Feed the Future Innovation Lab for Collaborative Research on Nutrition in Africa
Feed the Future Innovation Lab for Small Scale Irrigation
Feed the Future Innovation Lab for the Reduction of Postharvest Loss
Kansas State University
Michigan State University
North Carolina A&T State University
Oakland University
Pennsylvania State University
Stanford University
Texas A&M University
Tillers International
University of California, Davis
University of Florida
University of Illinois at Urbana-Champaign
University of Maryland
University of Tennessee Institute of Agriculture (UTIA)
University of Wisconsin – Madison

BANGLADESH

ACI Motors Limited
Bangladesh Agricultural Research Council (BARC)
Bangladesh Agricultural Research Institute (BARI).
Bangladesh Agricultural University
Bangladesh Rice Research Institute
BRAC
International Maize and Wheat Improvement Center (CIMMYT)
International Rice Research Institute (IRRI)
Khulna University

BURKINA FASO

Association pour la Promotion de l'Elevage en Savane et au Sahel (APESS)
Institut de l'Environnement et de Recherches Agricoles (INERA)
International Livestock Research Institute (ILRI)
La Fédération Nationale des Groupements Naam (FNGN)
Polytechnic University of Bobo-Dioulasso (UPD)
The International Union for Conservation of Nature (IUCN)

CAMBODIA

Agricultural Development Denmark Asia
AVRDC — World Vegetable Center
Conservation Agriculture Service Center (CASC)
Department of Agricultural Engineering (DAEng)

ECHO Asia
Institute of Technology of Cambodia (ICT)
Kasetsart University
Ministry of Agriculture Forestry and Fisheries (MAFF)
Ministry of Education and Youth (MoEY)
Royal University of Agriculture - Phnom Penh
University of Battambang

ETHIOPIA

Africa Research in Sustainable Intensification for the Next Generation (Africa RISING)
Bahir Dar University / Bahir Dar Institute of Technology
International Food Policy Research Institute (IFPRI)
International Livestock Research Institute (ILRI)
International Water Management Institute (IWMI)
University of Twente

MALAWI

Lilongwe University of Agriculture and Natural Resources (LUANAR)

SENEGAL

Institut Sénégalais de Recherches Agricoles (ISRA) – Centre National de Recherches Agrinomiques de Bambey (CNRA – Bambey)
ISRA - Laboratoire National de Recherche sur les Production Vegetales (LNRPV)
ISRA - Laboratoire National d'Élevage et de Recherches Vétérinaire (LNERV)
University of Thies – College of Agriculture
Institut de Technologie Alimentaire (ITA)
Agence Nationale de Conseil Agricole et Rural (ANCAR)
Réseau des Organisations Paysannes et Pastorales du Sénégal (RESOPP)
Institut de Recherche Pour le Développement (IRD)
Centre de Coopération Internationale en Recherche Agronomique pour le Développement (CIRAD)
Conseil ouest et centre africaine pour la recherche et le développement agricoles (CORAF)

TANZANIA

Sokoine University of Agriculture (SUA)
Wageningen University and Research Center
International Center for Tropical Agriculture (CIAT)
Nelson Mandela African Institution of Science and Technology (NM-AIST)
International Institute of Tropical Agriculture (IITA)
Africa Research in Sustainable Intensification for the Next Generation (Africa – RISING)
International Maize and Wheat Improvement Center (CIMMYT)
N2Africa

ADDITIONAL PARTNERS OR COLLABORATORS

International Institute for Applied Systems Analysis (IIASA)
ITC – Netherlands
Kifiya Financial Technology Plc.
One Acre Fund
Quantitative Engineering Design
Swisscontact
Taking Maize Agronomy to Scale in Africa (TAMASA)
Wageningen University and Research Center
World Agroforestry Center

ACRONYMS

ACIAR — Australian Centre for International Agricultural Research
ADDA — Agricultural Development Denmark Asia
ADS — Automated Directives System
Africa RISING — Africa Research in Sustainable Intensification for the Next Generation
AfSIS — Africa Soil Information Service
AGRA — Alliance for a Green Revolution in Africa
ANCAR — Agence Nationale de Conseil Agricole et Rural
AOR — Agreement Officer's Representative
APESS — Association pour la Promotion de l'Elevage en Savane et au Sahel
ASA — American Soybean Association
ASM — Appropriate Scale Mechanization
ASMC — Appropriate Scale Mechanization Consortium
AUC — African Union Commission
AWP — Annual Work Plan

BARC — Bangladesh Agricultural Research Council
BARI — Bangladesh Agricultural Research Institute

CA — Conservation Agriculture
CASC — Conservation Agriculture Service Center
CASF — Conservation Agriculture Service with a Fee
CAST — Commercialization of Aquaculture for Sustainable Trade
CE SAIN — Center of Excellence on Sustainable Agricultural Intensification and Nutrition
CGIAR — Consultative Group on International Agricultural Research
CIAT — International Center for Tropical Agriculture
CIMMYT — International Maize and Wheat Improvement Center
CIRAD — Centre de Coopération Internationale en Recherche Agronomique pour le Développement
CNRA — Centre National de Recherches Agronomiques (CNRA)
CORAF — Conseil Ouest et Centre Africain pour la Recherche et le Développement Agricoles
CSA — Climate Smart Agriculture
CSIRO — Commonwealth Scientific and Industrial Research Organisation

DAEng — Department of Agricultural Engineering
DDL — Data Development Library

EAB — External Advisory Board
EMMP — Environmental Management and Mitigation Plan

FAA — Federal Aviation Administration
FAO — Food and Agriculture Organization
FGD — Focus Group Discussions
FNGN — La Federation Nationale des Groupements Naam
FLMLA — Faculty of Land Management and Land Administration
FTFMS — Feed the Future Monitoring System
FY — Fiscal Year

GFC — Geospatial and Farming Systems Research Consortium

GIS — Geographic Information System
GMCC — Green Manure Cover Crops

HYV — High Yielding Varieties
ICRISAT — International Crops Research Institute for the Semi-Arid Tropics

ICT — Institute of Technology of Cambodia
IDRC — International Development Research Centre
IDSS — Integrated Decision Support System
IFDC — International Fertilizer Development Center
IFPRI — International Food Policy Research Institute
IIASA — International Institute for Applied Systems Analysis
IITA — International Institute of Tropical Agriculture
IL — Innovation Lab
ILRI — International Livestock Research Institute
ILSSI — Innovation Lab for Small Scale Irrigation
INERA — Institut de l'Environnement et de Recherches Agricoles de Burkina Faso
INGENAES — Integrating Gender and Nutrition within Agricultural Extension Services
IPM — Integrated Pest Management
IRD — Institut de Recherche Pour le Développement
IRRI — International Rice Research Institute
ISRA — Institut Sénégalais de Recherches Agricoles
ITA — Institut de Technologie Alimentaire
IUCN — International Union for Conservation of Nature
IWMI — International Water Management Institute

LIVES — Livestock and Irrigation Value Chains for Ethiopian Smallholders
LNERV — Laboratoire National d'Élevage et de Recherches Vétérinaire
LNRPV — Laboratoire National de Recherche sur les Production Vegetales

MAFF — Ministry of Agriculture Forestry and Fisheries
ME — Management Entity
MoEY — Ministry of Education and Youth
MSU — Michigan State University

NARS — National Agricultural Research Systems
NGO — Nongovernmental Organization
NM-AIST — Nelson Mandela African Institution of Science and Technology
NUS — Neglected and Underutilized Species

PRC — Policy Research Consortium
PI — Principal Investigator
PTOS — Power Tiller Operated System
R4D — Research for Development
RESOPP — Réseau des Organisations Paysannes et Pastorales du Senegal
RHoMIS — Rural Household Multiple Indicator Survey
RUA — Royal University of Agriculture

SAR — Synthetic Aperture Radar
SBIR — Small Business Innovation Research

SI — Sustainable intensification
SIIL — Sustainable Intensification Innovation Lab
SIPS — Sustainably Intensified Production Systems
SSA — Sub-Saharan Africa
SUA — Sokoine University of Agriculture

TAMASA — Taking Maize Agronomy to Scale in Africa
TP — Technology Park

UAV — Unmanned Aerial Vehicle
UBB — University of Battambang
UPB — Polytechnic University of Bobo-Dioulasso
USAID — United States Agency for International Development
USG — United States Government
UTIA — University of Tennessee Institute of Agriculture

WAgN — Women in Agriculture Network

TABLE OF CONTENTS

PROGRAM GOALS AND OBJECTIVES

The Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) serves is a global leader in interdisciplinary research, knowledge sharing and capacity building on sustainable intensification (SI). SIIL supports a strategic portfolio dedicated to identifying, characterizing, and developing pathways out of hunger and poverty for smallholder families through sustainable agricultural intensification—a process by which farm productivity is increased on existing farmlands, while promoting efficient and resilient farming systems that conserve or enhance environmental capital. SIIL's portfolio integrates socio-economic and biophysical factors to explore barriers of adoption to augment its SI farming systems research to enhance productivity, resilience, and improve nutrition.

SIIL includes eight major components:

(1) Portfolio of research projects studying the development and implementation of SI practices in seven countries in three regions West Africa (Senegal and Burkina Faso), East Africa (Tanzania, Malawi, and Ethiopia) and Southeast Asia (Bangladesh and Cambodia), https://www.k-state.edu/siil/whatwedo/.
(2) **Geospatial and Farming Systems Research Consortium** (GFC) led by the University of California, Davis – the GFC works to link farming systems with geospatial approaches, www.gfc.ucdavis.edu.
(3) **Appropriate Scale Mechanization Consortium** (ASMC) led by University of Illinois at Urbana-Champaign – ASMC aims to intensify smallholder farmers' cropping systems and on-farm operations through mechanization in a sustainable manner and builds local capacity in Burkina Faso, Bangladesh, Cambodia, and Ethiopia, https://www.k-state.edu/siil/whatwedo/consortiums/mechanization/.
(4) **Policy Research Consortium** (PRC) led by Rutgers University – the PRC conducts research on developing and utilizing specific set of indicators to quantify the impact or progress towards food and nutritional security, http://ru-ftf.rutgers.edu/.
(5) **Center of Excellence on Sustainable Agricultural Intensification and Nutrition** (CESAIN) in Cambodia led by the Royal University of Agriculture. CESAIN improves food and nutritional security in Cambodia by supporting agricultural research, education, extension and fostering private sector engagement, www.cesain.org.
(6) **Sustainable Intensification (SI) Assessment Framework** is an interactive method to assess research in sustainable intensification and adapt practices to achieve the best possible outcome for all aspects of a smallholder farmer's system, https://sitoolkit.com/
(7) **Research Output Dissemination Study** (RODS) led by University of California Davis. The RODS study evaluates the path from the development to end-user for selected innovation/technologies produced by the Feed the Future Innovation Labs, https://caes.ucdavis.edu/outreach/geo/projects/past/SIILRODS.
(8) **Sustainable Opportunities for Increasing Livelihoods with Soils** (SOILS) Consortium led by the International Fertilizer Development Center (IFDC). The SOILS consortium improves the health and fertility of soils as the foundation for nutritious food production and resilient and sustainable livelihoods, www.ifdc.org.

OVERVIEW OF PROGRAM ACTIVITIES

Activity: Administration

This report presents progress over the first five-year phase of the Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL). The five-year phase of the Sustainable Intensification Innovation Lab began on September 15, 2015 and concluded on September 14, 2019. Kansas State University hosts the Sustainable Intensification Innovation Lab in the College of Agriculture. The primary goal of the management entity (ME) is to develop a portfolio of research activities, combined with human and institutional capacity development, to improve human and institutional capacity building through the promotion of integrated farming systems in target countries. An external advisory board serves a managerial role in the selection, overview and evaluation of projects and provides advice on programmatic direction and management. Table 1 presents the management team and external advisory board members. The USAID Agreement Officer's Representative is Dr. Jerry Glover.

Table 1. Management Entity Staff and External Advisory Board Members

Management Entity		**External Advisory Board**
Director	Dr. P.V. Vara Prasad	Dr. Jules Pretty (Chair)
Associate Director	Dr. B. Jan Middendorf	Dr. John Dixon
Research Professor	Dr. Manny Reyes	Dr. Cornelia Flora
Research Assistant Professor	Dr. Zachary Stewart	Dr. Jemimah Njuki
Research Assistant Professor (2016-19)	Dr. Jessie Vipham	Dr. Peter Thorne
Program Administrator	Andra Williams	Dr. Deborah Bossio
Program Coordinator (2015-18)	Molly Webb	
Business Manager	Jessica Burden	
Business Manager (2015-19)	Katy Bach	

Additionally, as a part of the management of each project, consortium or region, a lead principal investigator (PI) or coordinator was charged with making the programmatic decisions based on the proposals submitted to the SIIL ME in 2014. Table 2 presents the PIs and coordinators that worked with SIIL on the various components of their portfolio.

SIIL Management Entity Staff


Prasad


Middendorf


Reyes


Vipham


Stewart


Bach


Williams


Burden

External Advisory Board


Pretty


Dixon


Flora


Njuki


Thorne


Bossio

Table 2. SIIL Project and Country Coordinators

Project/Country	**PI/Coordinator**
Appropriate Scale mechanization Consortium – University of Illinois at Urbana-Champaign	Dr. Alan Hansen
Center of Excellence for Sustainable Agricultural Intensification and Nutrition – Royal University of Agriculture, Cambodia	Dr. Lyda Hok
Geospatial and Farming Systems Research Consortium – University of California, Davis	Dr. Robert Hijmans
Research Output Dissemination Study – University of California, Davis	Dr. Nancy Allen
Policy Research Consortium – Rutgers University	Dr. Carl Pray
"Sustainable intensification through better integration of crop and livestock production systems for improved food security and environmental benefits in Sahelian zone" - Burkina Faso	Dr. Augustine Ayantunde
"Adoption of Sustainable Intensification in Dual-Purpose Millet - Leguminous Crops - Livestock Systems to Improve Food and Nutritional Security and Natural Resources Management for Rural Smallholder Farmers" – Senegal	Dr. Doohong Min
"Unlocking the production potential of 'polder communities' in coastal Bangladesh through improved resource use efficiency and diversified cropping systems" – Bangladesh	Dr. Krishna Jagadish
"Evaluation of the Relationship Between Sustainably Intensified Production Systems (SIPS) and Nutritional Outcomes (SIPS-NO)" – Ethiopia	Dr. Neville Clarke
"Women in Agriculture Network (WAgN)" - Cambodia	Dr. Rick Bates
"Raising crop response: bidirectional learning to catalyze sustainable intensification at multiple scales" - Tanzania	Dr. Sieglinde Snapp
Regional Coordinator – East Africa (2015 – 2019)	Jovin Lwehabura
Country Coordinator – Senegal	Dr. Aliou Faye
Country Coordinator – Burkina Faso	Dr. Hamidou Traore

Activity: Long-term Training

As a part of the on-going effort of the SIIL to build both human and institutional capacity in its focus countries, they supported students in a variety of higher education programs. From 2014-2019, the SIIL supported (fully or partially) a total of 115 students pursuing degrees in agronomy, food science, gender studies, soil science, water management, and others having to do with agriculture and food security. Of the 115, 70 were men and 45 (39%) were women, with 6 Bachelor's degrees, 61 Master's degrees and 48

PhDs being pursued. Additionally, several received national or international recognition for their accomplishments while conducting their research:

Student Awards and Recognitions

- Semi-Finalist, *'The Geneva Challenge 2018' - Advancing Development Goals International Contest, Graduate Institute of International and Development Studies, The Graduate Institute of Geneva* – Mohammad Ali, MS in Agricultural Economics, Bangladesh Agricultural University, 2018
- 2018 International Rice Research Institute Young Scientist Award, *5th International Rice Congress 2018, Singapore* – Aaron Shew, PhD in Environmental Dynamics, University of Arkansas, 2018 (currently the R.E. Lee Wilson Chair of Agricultural Business at Arkansas State University)

Activity: Short-term Training

Another aspect of SIIL's capacity-building efforts were the in-country short-term trainings given by the projects in the focus countries as they related to the activities they were conducting. In total, from 2014-2019, SIIL project partners conducted 268 individual training workshops for 13,456 participants, with women making up an average of 37% of those participants, on a variety of topics.

2015	Proposals submitted and projects launched; no trainings conducted		
2016	Total trainings:	10	
	Individuals trained:	684	(30% female, 70% male)
2017	Total trainings:	53	
	Individuals trained:	2264	(39% female, 61% male)
2018	Total trainings:	99	
	Individuals trained:	4336	(35% female, 65% male)
2019	Total trainings:	106	
	Individuals trained:	6172	(39% female, 61% male)

Activity: Institutional Development, Collaboration and Networking

During its first five-years, the SIIL put in place numerous agreements with various national and international organizations, educational institutions and research entities to allow for cooperation on a variety of levels, via subawards, associate awards, memorandums of agreement (MOA) and memorandums of understanding (MOU). These include the Institut Sénégalais de Recherches Agricoles (ISRA), where SIIL has supported agricultural research and long-term trainees; the Royal Agricultural University in Cambodia, where many SIIL-funded Cambodian scholars have received degrees and where CE SAIN is currently being housed; the International Rice Research Institute in Bangladesh, which has partnered with the SIIL polder project to train local farmers and extension workers on improved crop varieties and planting techniques; and the International Center for Tropical Agriculture (CIAT), which worked with both the Tanzania and Malawi projects to improve agriculture and food security in East Africa.

The SIIL recognizes that its mission and goals during the first five-years could not have been achieved without the assistance of its many partners and collaborators around the world. The ME remains committed to both working with its existing partners and seeking out new ones during its second five-year phase.

Activity: Annual Meetings and Other Events

Annual Meetings

The SIIL has held annual meetings from 2016-2019 at Kansas State University in Manhattan, KS, where the ME is housed, as well as in Cambodia and Senegal, as a way to showcase SIIL-funded projects in those countries. Each meeting had a theme that spoke to both the SIIL mission and the part of the SIIL journey that the ME wished to emphasize at the time (e.g. "Collaborate, Learn, and Adapt", "Suitability, Scalability, Sustainability"). They were attended by representatives and partners from the United States Agency for International Development (USAID), educational and governmental institutions, and the private sector, as well as local and international NGOs and development agencies. A few highlights from those meetings include:

- The First International Sustainable Agricultural Intensification and Nutrition (SAIN) Conference – January 12-13, 2018, Kampong Thom and Siem Reap, Cambodia
  - Included discussions and presentations on sustainable agricultural intensification, food security, and nutrition, as well as visits to SIIL partner the Royal University of Agriculture and Technology Parks.
- Site visits to Bambey Serer High School and PASTEF Women's Cooperative – April 10, 2019, Bambey and Malicounda, Senegal
  - Showcased activities in dual-purpose millet (bio-fortified and nutritionally enhanced for human consumption) and improved chicken production by the women's cooperative, and conservation agriculture training at the high school.

Other Events and Conferences

- Co-Creation Event of CE SAIN Development and Cambodia SWOT Analysis (Battambang and Phnom Penh, Cambodia, April 7-9, 2015)
- Rwanda SWOT Analysis for Climate-Smart and Geospatial Projects (Kigali, Rwanda, August 20-21, 2015)
- Soil Fertility Summit (Dakar, Senegal, August 14-15, 2017)
- World Food Prize Peace Corps Panel (Des Moines, Iowa, October 17, 2018)
- iREACH Co-Creation Dialogue (Somone, Senegal, September 9-10, 2019)
- SIAF Trainings (Cambodia, April; Senegal, April 27-29, 2017)
- Peace Corps Training – March 20-24, 2018; Dec 11, 2019 (Master Farmer Conference)

Activity: Private Sector Engagement

SIIL, though its various partners and partnerships, engaged with a number of private sector organizations to manufacture and extend innovations and technologies designed to increase resilience and better the livelihoods of smallholder farmers in the focus countries. These organizations include:

- Bangladesh:
  - ACI Motors Ltd. – provided workshops materials for the regional symposium in 2017 and 2018 and provided their machines for scaling up the identified technologies
  - The Metal Pvt. Ltd. – provided their machines for scaling up the identified technologies

- Cambodia:
  - Smart Agro – they have been in operation for a few years and produce cover crop seeds. With the support of CASF, MIGIP and future projects, S3 and ASMC, there will be promotion and dissemination activities.
  - Larano – a manufacturing workshop that has imported the first commercial shipment of no-till seeders from Brazil. MIGIP, S3 and ASMC will be supporting the promotion of land planers and no-till planters.

- Neourn – a manufacturing workshop that promotes fertilizer and seed spreaders that have been researched by ASMC. They are supported by MIGIP and ASMC.
- Swisscontact – while not a private entity, this Swiss NGO operates in two working areas – enterprise promotion, skills development – to promote development through the private sector. Building on the wider organization's regional and global experience, Swisscontact strives to support local areas of focus, including agricultural innovation, tourism, impact investment, and renewable energy.

- Ethiopia:

  - Ergo-Tech (U.S. based private company from Dr. Brian Lilly, UIUC professor) – Sold us 50 maji pumps to conduct research trials in water lifting technologies. Dr. Lilly provided trainings on how to use it and perform basic maintenance to entrepreneurs, university faculty, graduate students, and farmers. Additionally, part of the 50 maji pumps were given in loan to farmers so they can use them to create awareness so the farmers can purchase them later.
  - Cleber LLC (Manufacturing company of Oggun tractors which is based in the U.S.) – Hosted in 2019 our Ethiopian team to show them their manufacturing plant and tractor capabilities and how to build them
  - Amish Companies from Pennsylvania (All of them showed their equipment that is used with animal draft power) –
    - I&J Manufacturing LLC: Farm machinery
    - The White Horse Machine LLC: Farm machinery
    - NOLT'S Produce Supplies Center: Micro irrigation business

Activity: Gender and Nutrition Integration Efforts

The SIIL is committed to improving the human condition as a part of its mission statement, which includes reduction of drudgery for women and children, woman's empowerment in the agricultural sector, and gender equity overall. As a part of these efforts, in-country partners across our focus countries held training workshops, conducted surveys and focus groups, and held interactive field days to raise awareness about the need to increase gender awareness and sensitivity in agriculture, nutrition and household decision-making. Additionally, projects worked hard to fund women who wished to pursue their higher education degrees, both in the US and in their home countries. Highlights include:

- The WAgN project saw one student, Saovanneary Huot, defend her M.S. thesis this in Fall 2019 at Penn State University, and she entered into Penn State's PhD program in Spring 2020, where she is studying Rural Psychology.
- In a study conducted by SIPSIN, the gender equity and women empowerment analysis, based on IFPRI surveys, showed preliminary results that suggest women in Ethiopia did better in terms of their input in decisions about irrigated cash crop farming after small-scale irrigation interventions than before.
- In 2018, the Geospatial and Farming System Research Consortium submitted a paper for publication on the Female Empowerment Index (FEMI) that tracks multiple domains of women's empowerment and can be used to assess both national and sub-national variation. The index was developed using data for Nigeria (very data rich) and are now applying it for all of sub-Saharan Africa.
- In 2019, a paper was submitted by the Tanzania project that documented the current status of child feeding practices and how to improve them, based on a household survey and sampled food

portions analyzed for aflatoxin: '*Monotonous Cereal Based Complementary Feeding Contributes to Aflatoxin Exposure in Children*'.

- Fatou Tine, a graduate student supported by the Dual-Purpose Millet project in Senegal, was hired by the Peace Corps as Agriculture Volunteer Trainer, in 2019.

Activity: Knowledge Sharing and Management

Project-Generated Publications through Subawards and Consortiums (peer-reviewed journal articles, presentations, dissertations and data sets) – 342 total.

	Peer-reviewed articles	Presentations	Dissertations/Theses	Data Sets
2015	Proposals submitted and projects launched; no publications produced			
2016	0	9	0	6
2017	11	10	4	13
2018	14	35	8	11
2019	113	36	33	39
Total	138	90	45	69

During this same timeframe (2014-2019), the Management Entity generated 40 peer reviewed journal articles and reports in connection with Feed the Future funding and SIIL. All publication citations are in Appendix A.

Additional Publications
- SWOT Analyses: Bangladesh, Cambodia, Rwanda, Tanzania
- Research Output Dissemination Study (RODS) report
- Soil Fertility Reports
- SIIL Annual Reports: 2016, 2017, 2018, 2019
- Success stories: see reports below for country-specific success stories
- Blog: 71 posts on SIIL website

Activity: Utilization of Outputs – Scaling Technology Packages

During the first five years of the SIIL's existence, the research funded by the Lab produced a total of 28 unique technologies (see complete list in Appendix B), from improved mechanical products that could be made locally and inexpensively, to better yoke designs that increased animal comfort, to dual-purpose millet varieties that were bred specifically for improved nutritional content for both human and animal consumption. Below are a few examples of the technologies the SIIL helped fund during its first phase:

- Drip irrigation system using solar powered pumps designed to minimize labor and increase crop yields and income generation (SIPSIN, Ethiopia)
- Grafting technology taking tomatoes and grafting them onto local eggplant rootstock to allow for tomatoes to be grown during the wet season (WAgN, Cambodia)

- Digital technology to track malaria hotspots by mapping mosquito breeding suitability (Precision Agriculture for Smallholder Systems in Africa, Malawi)
- Dual-purpose pearl millet varieties whose leaves maintain greenness after grain maturity and had higher grain yields (Dual-Purpose Millet, Senegal)
- Resilient cropping patterns for the polder ecosystem to increase yields during both wet and dry seasons (Unlocking the Production Potential of Polder Communities, Bangladesh)

A woman participates in mechanical harvesting in a field in Bangladesh.

FUTURE CHALLENGES AND OPPORTUNITIES

The SIIL has been granted a five-year funding extension by USAID until September 15, 2024. This second phase of the lab will be an opportunity to take the progress and achievements from the first phase and begin scaling them up in ways that will help smallholder farmers become more resilient in the future. The SIIL Management Entity has reviewed and accepted proposals from the continuing projects, and looks forward to working with them to accomplish the goals set out in their scopes of work.

The SIIL has also partnered with the Conseil Ouest et Centre Africain pour la Recherche et le Développement Agricoles (CORAF) and USAID to implement the Innovation, Research, Extension and Advisory Coordination Hub (iREACH) initiative in West Africa. iREACH will be piloted in Senegal, with eventual satellites in Burkina Faso, Ghana, Niger and Mali, and will focus on addressing then need for increased access to promising innovations and a technologies across the West Africa region through the creation of technology parks in the target countries. Additionally, iREACH address building human and institutional capacity, and work to improve alignment and integration of relevant activities.

In light of the COVID-19 pandemic, many partner institutions and organizations have scaled back activities relating to SIIL projects. While there were no major setbacks during the first five-year phase due to the pandemic, there may be some future disruptions in the project timelines as each country, organization, or institution handles the situation differently. However, the major disruptions caused by COVID-19 have also presented SIIL with an excellent opportunity to assess how smallholder farmers, businesses and other organizations being targeted by SIIL's work are reacting to the changes. Building resilience among smallholder farmers a major component of the SIIL mission, and this challenge will be a real-life test of how well the programs are promoting and increasing that though their activities. The SIIL looks forward to designing and implementing new technologies and survey instruments to access and increase resilience among its target populations.

ACCOMPLISHMENTS: INDIVIDUAL PROJECT REPORTS

Individual project reports can be found in this next section by each individual country. There is a comprehensive description of each project from the first five years of the SIIL's work. The countries are:

- Senegal
- Burkina Faso
- Ethiopia
- Malawi
- Tanzania
- Bangladesh
- Cambodia

SENEGAL

West Africa
Senegal

Sustainable Intensification in Dual-Purpose Pearl Millet-Leguminous Crops-Livestock Systems to improve Food and Nutritional Security and Natural Resources Management for Rural Small Holder Farmers in Senegal

1. **Lead Institution:** Kansas State University (KSU)
   - International Collaborating Institution
     - Institut Senegalais de Recherches Agricoles (ISRA)
     - Centre National de Recherches Agronomiques de Bambey (CNRA/Bambey)
     - University of Thies
     - Institut de Technologie Alimentaire (ITA)
     - Agence Nationale de Conseil Agricole et Rural (ANCAR)
     - Le Réseau des Organisations Paysannes et Pastorales du Sénégal (RESOPP)

2. **Research Team:**
   - Lead Investigator:
     - Doohong Min, KSU
   - Co-Investigators:
     - Ousmane Sy, ISRA-CNRA
     - Aliou Faye, ISRA-CNRA
     - Mamadou Diaw, ENSA
     - Moussa Sall, ISRA-BAME
     - Fallou Sarr, ITA
     - Bintou Dieye, ANCAR
     - Ablaye Ndour, RESOPP
     - Laurent Laplaze, IRD
     - Jonathan Vayssieres, CIRAD

3. Executive Summary

Africa's population is growing fast, reaching about 2.4 billion (about 20% of the world population) by 2050. To feed this growing population, protein sources such as meat and milk will play a critical role in terms of improving nutritional status, particularly for women and children.

The proposed project was focused on "Sustainable Intensification in Dual-Purpose Pearl Millet-Leguminous Crops-Livestock Systems to Improve Food and Nutritional Security and Natural Resources Management for Rural Small Holder Farmers in Senegal." The main objective of this project was to ensure food and nutritional security, establish resilient farming systems (via a holistic approach for rural smallholder farmers, particularly women), and improve nutritional and socio-economic status, particularly for women and children. A value chain approach was used by integrating agronomy, livestock, socio-economic, human food nutrition and gender via field/lab research, on-farm trials, surveys, and short and long-term trainings. Traditionally, pearl millet varieties have been used mainly for grain purposes.

> Millet is the most important staple cereal crop in Senegal due to good adaptation to high temperatures, severe drought conditions and soil types in most regions of Senegal. Many varieties of millet have been used as grains and/or raw materials for roofs or fences of homes in rural areas in Senegal.

However, new dual-purpose pearl millet varieties (i.e., SL 28, 169, and 423) opened up a door of opportunity to be used as both grain and fodder. In terms of phenotype, dual-purpose millet varieties showed bigger and longer seed head and larger stem size than local millet varieties and stovers maintained the greenness even after grains ripen, which resulted in some attention and interest by local farmers who attended field days. We were able to show that combining half the recommended rate of mineral fertilizer with compost on pearl millet gave the same yield as the recommended mineral fertilizer rate for this crop. Also, intercropping a legume crop into the pearl millet row did increase the overall production of the system. Dual-purpose pearl millet varieties had significantly higher stover yield than local pearl millet varieties. This finding could be attractive to the local livestock farmers who always experience feed/fodder shortage. In addition to higher stover yields, dual-purpose pearl millet stovers had higher forage nutritive value than local varieties so that feeding dual-purpose millet stovers could improve animal performance while using grains for human food. When averaged across dual-purpose pearl millet varieties, the minerals (Fe, K, Zn, Mg, P, and Ca), amylose, and protein were higher than control local variety (no name). In particular, the difference between dual-purpose millet vs. local variety was more significant in Fe and K minerals. This could help reduce children's malnutrition issues in Senegal.

For the long-term training over the last 4-year period, 9 Ph.D. and 23 master's graduate students (either Senegalese or African) finished or are finishing their degrees. Over 15 short-term trainings, including scientific paper writing and statistics, were organized for students, scientists and technicians. For the short-term trainings, more than 500 farmers (40% women) have attended Farmer Field Days; more than 400 farmers (80% women) were trained on both human and animal use of pearl millet; five women organizations have received small equipment for processing, and six hen-houses were installed for three of the women organizations. One of the biggest accomplishments was an awareness of dual-purpose pearl millet varieties. Each year (2017, 2018, 2019) over 46 demonstration plots were installed in 15 districts and villages, and 143 producers were directly involved, including 61 women. More than 2,840 producers were indirectly affected through exchange visits, trainings and awareness. Communication and information sessions were conducted on the varieties introduced in a peasant environment: twelve exchange visits with 512 participants. Trainings and women's transformation activities include 100 women trained on infant flour diet production and 30 actors trained on treating the pearl millet stovers with urea. A new partnership was also developed between local producer organizations and processing institute (i.e., ITA, institute of food technology).

Based on four-year research, outreach and capacity building, it appears this sustainable intensification of dual-purpose pearl millet-based crop livestock systems showed good potential to help rural smallholder crop and livestock farmers, particularly women in Senegal including several technologies that could be amplified in the second phase. This would ultimately help improve food and nutritional security and resilience while minimizing the environmental impacts under climate variability/extremes in Senegal.

4. Project Partners

An integral part of this project was to collaborate among agronomists, livestock specialists, socio-economists, human nutritionists, gender specialists, farmers and farmers cooperative in Senegal by overarching trans-disciplines and sharing the data and information as much as they can.

5. Project Goals and Objectives

Overall Goal

The overall goal of this project was to intensify the sustainability and resilience of farming systems, and improve human nutrition by integrating dual-purpose millets-leguminous crops-livestock in small-holder farmers under climate change/variability in Senegal.

Overall Objectives

Specific objectives related to each domain were:

Objective 1/Agronomy: To assess dual-purpose pearl millet varieties as grain and fodder, and identify the best management practices of growing dual-purpose millets under climate change/variability in Senegal.

Objective 2/Livestock: To increase animal performance by using fodder (stovers from millet, cowpea and groundnut) from dual-purpose millet stovers and leguminous crops in smallholder farms.

Objective 3/Socio-economic: To analyze farmer's causes and consequences of adopting dual-purpose millet, intercropping dual-purpose millet into leguminous crops such as cowpea and groundnut, and integrating with livestock.

Objective 4/Human Food Nutrition: To formulate and implement a project on dual-purpose millet use for grain with leguminous crops (i.e., cowpea and groundnut), ensure the processing and nutritional value of grain for human food consumption, and create diet diversity using dual-purpose pearl millet grain.

Objective 5/Gender: To improve women's gender equity and competency in the value chain of dual-purpose millet-leguminous crops-livestock integration in smallholder farmers in Senegal.

6. Overview of Activities

Research

Research activities conducted in both a field and lab include: dual-purpose millet seed multiplication, agronomic field trials in intercropping with leguminous crops (i.e., cowpea and groundnuts) and nitrogen input such as chemical fertilizer and animal manure; nutritive value analysis of dual-purpose millet stovers and conservation methods (i.e., hay and silage); possibilities of increasing sowing density with adapted fertilizer recommendation; identification of the most economically and socio-economically viable technologies, depending on the study area based on the analysis of quantitative (station and farmland) and qualitative (including producer perceptions of different dual-use millet technologies; biochemical analysis of dual-purpose pearl millet grain and diet development for infants. Other activities from IRD: Our activities were performed through 2 Ph.D., one (Awa Faye) funded by the SIIL and one (Marie-Thérèse MOFINI) funded by the DAAD. During her Ph.D., Awa FAYE developed a method to quantify the 3D distribution of pearl millet roots in the soil in field conditions. She then used this technique to analyze the impact of drought stress and underground competition for resources (water and nutrients) when increasing pearl millet planting density on root system development. Another female student, Marie-Thérèse MOFINI evaluated the diversity of arbuscular mycorhizal fungi (AMF) present in the root of dual-purpose millet using a participative approach. Souna3 seeds were provided to farmers from 3 locations in Senegal situated along a rainfall gradient (from North to South: Darou Mousty, Dya, and Nioro). She then collected root and soil samples from their fields at the end of the growing season. We collected information on the growth technique (prior culture, fertilization, etc.). She also collected roots from wild pearl millets growing close to the studied fields to compare AMF diversity. In total 50 samples were collected. Soil samples were sent to the LAMA laboratory for composition analysis (C, N, P and K content, pH, etc). In parallel, AMF infection was analyzed on the root samples and DNA was extracted from roots. DNA samples were used for the amplification of a fungal marker to study the diversity of fungi by massive sequencing (metabarcoding).

Women processing and preparing millet. *Photo credit: Madame Dieye Bineta.*

Communication

ANCAR is in charge of gender-sensitive issues in the process of adoption of dual-use millet integration systems by the population and carried out awareness and information workshops on the project including awareness and communication activities through farmer field days at the demonstration plots in research stations and at the farmer level. The aim is to reduce the information gap between men and women but also to better consider the needs and preferences of men and women in the varietal selection of millet. Several farmer field days were organized at ISRA / CNRA Bambey, research stations Sinthiou Malem and Nioro but also in rural areas: Diourbel (Kane Kane, Ngoye, Ndoldol), Kaolack (Sibassor, Djilor, Diossong), Fatick (Passy) Kaffrine (Kougueul) Thiés (Fandéne, Méouane).

Capacity Building

Short-term training: A series of training sessions were organized for project beneficiaries in the Thies, Louga, Diourbel, Kaolack, Kaffrine, and Tamba regions. The objective pursued through these trainings was to strengthen the beneficiaries' capacities on the human and animal uses of millet per the objectives of the project which are the selection of dual-use millet varieties. Training themes developed during the four years of project implementation are: training on silage techniques, preservation techniques of millet straw with urea, a processing millet into enriched flour, a millet production technique for poultry feed and youth entrepreneurship for seed production arranged by RESOPP

Long-term training: Twenty-three master's and 9 Ph.D. students were either trained or are ongoing from the SIIL sponsored projects. Of these, Awa Faye, was a first SIIL female student who defended her Ph. D. at the UCAD in October 2019.

Support in Small Processing Equipment

To valorize the training on processing millet into enriched flour, small transformation equipment was offered to the beneficiary groups in the regions of Thies (Malicounda), Louga (Diokoul), Diourbel (Ndolndol and Kane Kane) and Tamba (Koussanar).

7. Accomplishments

Agronomy

In the past, traditional pearl millet varieties had mainly grain purpose. However, new dual-purpose pearl millet varieties (i.e., SL 28, 169, and 423) opened up a door of opportunity to be used as both grain and fodder. In terms of phenotype, dual-purpose millet varieties showed bigger and longer seed heads than local millet varieties, and stovers maintained the greenness even after the grains ripened, which resulted in some attention and interest by local farmers who attended field days.

We were able to show that combining half the recommended rate of mineral fertilizer with 2.5t/ha of compost on pearl millet gave the same yield than the recommended mineral fertilizer rate for this crop. Also, intercropping a legume crop into the pearl millet row did not have an effect on the yield but the overall production of the system increased. Therefore, this technique can be used by farmers to increase systems productivity and harvest diversity in smallholder farms in Senegal.

Livestock

Dual-purpose pearl millet varieties had significantly higher stover yield than local pearl millet varieties. This finding could be attracted by the local livestock farmers who always experience feed/fodder shortage. In addition to higher stover yields, dual-purpose pearl millet stovers had higher forage nutritive value than local varieties, so feeding dual-purpose millet stovers could also improve animal performance while using grains for human food.

Socio-Economic

According to farmers who were surveyed, dual-purpose millet performance and perception were different from region to region. For example, the SL 28 dual-purpose millet variety was profitable in all areas where Souna 3 is recommended. As part of this study, it is more recommended for the areas of Foundiougne, Bambey, Kébémer, and Sinthiou Malem. The latter is also a favorite for the profitable production of the SL 423 and the SL 169. The results of profitability and analysis of perceptions showed good profitability of the SL varieties especially the SL 169, in the zone of Bambey. The conditions offered by the department of Kébémer enhanced the performance of the Souna 3 and the SL 28 in terms of profitability. SL 28, SL 169 and Thialack 2 technologies are recommended for the Foundiougne department. For Kaolack, Thialack 2 and Souna 3 were recommended and for Nioro Thialack 2, SL 169 and Souna 3 were recommended. The Koungheul department was more favorable for Thialack 2. As for the zone of Sinthiou Malem, all the technologies performed well and the SL 423 performed the best under the best development conditions.

> Overall, the SL varieties combining large spike and stem size and staygreen traits with better forage quality have good potential to be scaled up. These easily visible features would allow for easier extension of dual-purpose millet technologies.

Nutrition

When averaged across all dual-purpose pearl millet varieties (i.e., SL28, SL169, SL423, and Thialack2), the minerals (Fe, K, Zn, Mg, P, and Ca), amylose, and protein were higher than control variety. In particular, the difference between dual-purpose millet vs. local variety was more significant in Fe and K minerals.

ANCAR

More than 500 farmers (40% women) have attended farmers' field days; More than 400 farmers (80% women) are trained on human and animal use of millet; five women organizations have received small equipment for processing and six hen-houses were installed for three women's organizations.

RESOPP

One of the biggest accomplishments was creating an awareness of dual-purpose pearl millet varieties among the local communities. The majority of local farmers had not heard of this new trait of pearl millet varieties before. However, they were exposed to the dual-purpose pearl millet by on-station/on-farm field days, farm visits and local media express. There was a diffusion of five varieties, three dual-purpose pearl millet varieties and two improved varieties (Thialack 2 and Souna 3) in comparison with local varieties (no name). Forty-six demonstration plots were installed in 15 districts and villages and 143 producers were directly involved including 61 women. More than 2,840 producers were indirectly affected through exchange visits, training, and awareness. Conducted communication and information sessions on the varieties introduced in a peasant environment: BAME, twelve exchange visits with 512 participants. Participated in satisfaction surveys with ISRA/BAME, training and women's transformation activities: 100 women were trained on infant flour diet production and 30 actors trained on treating the pearl millet stovers with urea. Development of new partnership between producer organizations and processing institute took place; Contract RESOPP with other farmers' organizations (URAP, FPKA) and formed partnerships with the university and Institute of Food Technology.

8. Utilization of Research Outputs

Below are the top technologies that can be scaled-up for smallholder farmers in Senegal based on the results from phase 1:

- Awareness of dual-purpose pearl millet varieties (i.e., SL 28, SL 169, and SL 423) for homologation will be promoted by testing these varieties with increasing acreages in different ecophysiological regions in Senegal and other West African countries that are in a similar biophysical and sociological conditions.

- The agronomic package on millet-based cropping intensification through increased sowing density and fertilizer actualization and improved organic farming system (legume intercropping and livestock manure application) will be utilized to scale up for the on-farm demonstrations. For example, farmers could use a combination of ½ compost and ½ mineral nitrogen fertilizer to increase their yield at the magnitude of the full rate of mineral fertilizer for pearl millet.

A dual-purpose millet plot at maturity. *Photo credit: Sy Ousmane.*

- Millet-based products will be scaled up for humans (women and infants) using dual-purpose millet grains. Millet stovers will be used at the farm levels in a feed form as hay, silage, or greenchop by measuring body weight gain or milk yield. Millet grain will be used as chicken feed (women and youth involved).

- The first first female Ph.D. student at IRD to be sponsored by the SIIL program, Awa Faye, created a tool (RACINE2.2) designed to extract pearl millet lines root system parameters and water acquisition estimates from measures in field conditions. It runs as an Excel sheet and will soon be made freely available online, with the full protocol written in English.

9. Future Challenges and Opportunities

- Expand awareness of dual-purpose pearl millet varieties to smallholder farmers in Senegal and other countries in West Africa.
- Support sustainable seed production of dual-purpose millet SL 28, SL 169 and SL 423 varieties for scale-up.
- Engage the Ministry of Livestock for wider dissemination of the dual-purpose millet varieties to smallholder farmers.
- Implement on-farm demonstration trials at both the model farms and other selected farms and collecting data from these farms accurately and reliably.
- The adoption of SI technologies should be accompanied by the availability of inputs even if in biomass production.
- A small-scale chopper intervention should happen for the smallholder farms to save their time and labor. This chopper technology would also improve feed intake and digestibility of small and large ruminant animals by chopping millet stovers into an optimum length with less energy spending on chewing. This could increase milk and meat production per unit animal, resulting in more farm income.
- Increase more on-farm feeding trials working with farmers and masters-level graduate students.
- Provide more trainings on an agronomic package of how to grow/manage/harvest dual-purpose pearl millet and grain-based product developments in particular led by women and youth.
- Promote the farmer-farmer school programs by connecting model farms with other local small-holder farmers to help build networking and exchange their dual-purpose millet farming experience and information.

10. Publications

1. Faye A., Sine B., Chopart J.L., Grondin A., Lucas M., Diedhiou A., Gantet P., Cournac L., Min, D., Audebert A., Kane A., Laplaze L. 2019. Development of a model estimating root length density

from root impacts on a soil profile in pearl millet (*Pennisetum glaucum* (L.) R. Br). Application to measure root system response to water stress in field conditions. *PLOS One*, 14(7): e0214182.

2. Sene S., M. Gueye, F. Sarr, Y. Diallo, M. Sow, A. Faye, D. H. Min, and M. Gaye. 2018. Parboiling Effect on Phytate Contains of two Senegalese pearl millet varieties (*Pennisetum glaucum* [L.] R.Br.) GB 87-35 and ICRITABI. J. Nutri. Health & Food Sci. ISSN Online: 2372-0980.
3. Ba, T., T. Diaw, T. Lo, D. H. Min, S. Dieng, O. Sy, A. Faye, A. Dieng. 2018. Characterization of the nutritional value of the upper and lower parts of the stems of three potentially dual-purpose millet populations in comparison with those of varieties Souna 3 and Thialack 2 in Senegal. J. Sci. & Eng. Res. 5 (9):338-349.

11. Datasets Produced

Datasets produced or being produced from graduate students will be uploaded as soon as they finish programs. Datasets location includes Bambey, Thies, Nioro and Sinthiou Maleme in Senegal.

Dataset	Repository	Notes
Soil raw data from Fatou Tine's Ph.D. work	SIIL Dataverse-Unpublished	This raw data is about soil pH, CEC, organic matter, total nitrogen, total carbon, and a ratio of total nitrogen to total carbon under different nitrogen sources (chemical fertilizer and compost) and leguminous crops (cowpea and groundnut).
Millet grain and biomass yield (Fatou Tine)	SIIL Dataverse-Unpublished	This raw data is about millet grain and biomass yield from a Ph.D. student's (Fatou Tine) work in Bambey and Nioro under different nitrogen sources (chemical fertilizer, compost, and a combination of ferilizer and compost).
Soil water content raw data	SIIL Dataverse-Unpublished	This raw data is about soil water content from Fatou Tine's work in different nitrogen sources such as chemical fertilizer and compost with leguminous crops (cowpea and groundnut).
Characterization of the nutritional value of the stems of millet	SIIL Dataverse-Unpublished	This study focused on the characterization of the nutritional value of the upper and lower parts of the stems of 3 millet populations assumed to be dual-use (SL28, SL169 and SL423) in comparison with the Souna 3 and Thialack 2 varieties.
Ph.D. student, Awa Faye's field root phenotyping data of pearl millet in Senegal	SIIL Dataverse-Unpublished	In this study, we developed a method to easily phenotype root system development in field trials. Our model predicts root length density (RLD) of

Dataset	Repository	Notes
		pearl millet plants from root intersection densities (RID) counted on a trench profile in field conditions.
Identification of dual access accessions of millet [Pennisetum glaucum (L.) R. Br.] From Burkina Faso, Mali, Niger and Senegal under the agro-ecological conditions of Senegal (Bambey & Nioro)	SIIL Dataverse-Unpublished	In this study, 100 pearl millet (Pennisetum glaucum (L.) R. Br.) accessions from four West African countries gene banks and from ICRISAT were evaluated for their grain and fodder performances. It aims at identifying dual purpose varieties with high grain yield, high iron and zinc contents and good quality of straw (digestibility, protein contains). It was performed during the 2016 raining season in station in two different agro-ecological zones (Bambey and Nioro).
Influence of nitrogen fertilization, millet / cowpea association and conservation techniques on the feed value of millet stems in Senegal	SIIL Dataverse-Unpublished	This study evaluated the effect of nitrogen fertilization, millet cowpea association and conservation techniques on nutritional value of three potentially dual-use millet populations (SL 28, SL 169 and SL 423) compared to registered varieties (Souna 3 and Thialack 2).
Analysis of factors in the adoption of new improved varieties of millet by producers in the groundnut basin of Senegal	SIIL Dataverse-Unpublished	The approach adopted during this study was to analyze the barriers to the adoption of improved varieties of millet by producers in the Groundnut Basin in Senegal.
Study of the digestibility of the lower and upper parties of the stems of three potential dual-purpose millet accessions using sheep	SIIL Dataverse-Unpublished	This is a thesis of a masters student who finished last April, 2017.

BURKINA FASO

West Africa
Burkina Faso

Sustainable Intensification through Better Integration of Crop and Livestock Production Systems for Improved Food Security and Environmental Benefits in Sahelian Zone of Burkina Faso

1. **Lead Institution**: International Livestock Research Institute (ILRI)
   - U.S. Collaborating Institution:
     - University of Wisconsin
   - International Collaborating Institutions:
     - International Union for Conservation of Nature (IUCN)
     - Institut de l'Environnement et de Recherches Agricoles (INERA)
     - Central and West Africa Program
     - Fédération Nationale des Groupements Naam (FNGN)
     - Association pour la Promotion de l'Elevage en Savane et au Sahel (APESS)

2. **Research team**:
   - Lead Investigator:
     - Augustine Ayantunde, ILRI
   - Co-Investigators:
     - Hadja Oumou Sanon, INERA
     - Mark van Wijk, ILRI
     - Matthew Turner, University of Wisconsin
     - Jacques Somda, IUCN

3. Executive Summary

The overall goal of this project was to improve household food production and nutrition and enhance ecosystem services through better integration of crop and livestock production systems in the Sahelian zone of Burkina Faso. The specific objectives were:

- To increase crop and livestock integration in these mixed systems, through improved crop production (dual-purpose sorghum and cowpea varieties), soil fertility (application of manure and inorganic fertilizer), water harvesting (zai and stone-bunding with vegetation strips) and livestock feed enhancing interventions (forage sorghum, dual-purpose cowpea, efficient feeding systems), all combined to lead to improved nutrition through increased consumption of animal-sourced food (milk).
- To assess the economic, social, nutritional and environmental benefits and tradeoffs of the productivity-enhancing interventions, and their potential for cost-efficient out scaling.
- To build the capacity of smallholder farmers and researchers on sustainable intensification through multi-stakeholders' platforms (e.g. FNGN, APESS); and to provide platforms (through FNGN and APESS) for learning from the so-called positive deviant farmers (those farmers who are doing better than their colleagues are with similar resources, and are more open to innovation) within the population.

The research activities were conducted in Seno and Yatenga provinces in Burkina Faso and the activities were implemented at both household and community levels. The main underlying hypothesis was that there is a great potential for the smallholder currently in crop-livestock systems to produce more per a given land area thereby improving productivity, food security and nutrition while preserving ecosystem

services. Accomplishments of the project included baseline characterization of 400 households in the projects sites including the constraints and opportunities for sustainable intensification, agronomic trails with improved dual-purpose cowpea (KVX 745-11P) and sorghum (Sariaso 16) varieties, survey on the influence of gender on intensification practices, the establishment of Farmers' Field School in project communities, tradeoff analysis of productivity-enhancing interventions, monitoring of household nutrition and growth of children between 6 and 36 months, qualitative and quantitative assessment of cost-benefit analysis of productivity-enhancing interventions, implementation of sustainable intensification assessment framework and building capacity of farmers, students and young researchers on sustainable intensification practices. The dual-purpose cowpea and sorghum varieties introduced by the project are being planted by the farmers in the project sites. To build capacity in the production of seed of the improved varieties, farmers from the project sites were trained by INERA. Farmers' associations such as FNGN, APESS are scaling the improved dual-purpose cowpea and sorghum varieties. From the project activities, many issues for future research include the following. (i) Adoption studies of the uptake of improved dual-purpose cowpea and sorghum varieties by farmers, and in-depth assessment of economic and nutritional benefits. (ii) Assessment of the effect of nutrition-sensitive livestock interventions on household food security and nutrition of children and reproductive women. (iii) Tradeoff analysis of productivity-enhancing interventions and their potential for cost-efficient scaling. (iv) Analysis of the influence of community-level factors such as resource tenure institutions, leadership structures on intensification practices and household nutrition.

> Generally, the intensification options were perceived to have a positive impact on food security in both project sites although the degree of the perceived impact varied with each intensification option and site.

4. Project Goals and Objectives

Overall Goal

The overall goal of this project on sustainable intensification through better integration of crop and livestock production systems in the Sahelian zone of Burkina Faso was to improve household food production and nutrition and to enhance ecosystem services through better integration of crop and livestock production systems in the Sahel region of Burkina Faso.

Overall Objectives

The specific project objectives were:

Objective 1: To increase crop and livestock integration in these mixed systems through improved crop production, soil fertility, water harvesting, and livestock feed enhancing interventions.

Objective 2: To assess the economic, social, nutritional and environmental benefits and tradeoffs of the productivity-enhancing interventions, and the potential for cost-efficient out scaling.

Objective 3: To build the capacity of smallholder farmers and researchers on sustainable intensification and improved nutrition through multi-stakeholders' platforms. The research activities are solution-focused to meet the needs of farmers and were implemented at both household and community levels in Seno and Yatenga provinces in the Sahelian zone of Burkina Faso with rainfall between 300 and 600 mm per year. The main underlying hypothesis was that there is a great potential for the smallholder farmers currently engaged in crop-livestock systems to produce more in a given area of land, thereby improving productivity, food security, and nutrition while preserving ecosystem services.

5. Overview of Activities

The project activities revolved around four results as presented below:

RESULT 1: Production of crop-livestock systems is improved and household welfare enhanced in a sustainable manner with higher crop yields, better quality fodder supply, increased consumption of animal-sourced food and higher income to smallholder farmers.

- **Activity 1:** Review opportunities and constraints for sustainable intensification in the Sahelian zone
- **Activity 2**: Baseline characterization of the study sites
- **Activity 3:** Participatory testing and evaluation of crop and livestock sustainable intensification innovations

RESULT 2: Social, economic, nutritional and environmental benefits and tradeoffs of productivity-enhancing crop and livestock interventions evaluated and shared with key stakeholders to inform a decision on the adoption of sustainable intensification innovations.

- **Activity 1:** Analysis of socio-economic aspects behind variation in natural resource management and nutritional status
- **Activity 2:** Gender analysis on the roles, livelihood strategies, constraints and preferences of men, women, and youth, and the marginalized groups in crop-livestock production in the study sites and the nutritional benefits of the interventions
- **Activity 3:** Cost-benefit analysis of productivity-enhancing interventions including labor productivity
- **Activity 4:** Tradeoffs analysis of productivity-enhancing intervention
- **Activity 5:** Quantify the livestock-water productivity of the focus crop-livestock production systems, and assess the effects of the different interventions on this LWP.

Result 3: Capacity of smallholder farmers and local institutions strengthened in best-fit sustainable intensification innovations and improved nutrition through multi-stakeholder platforms, practical training and co-learning and strengthening of the capacity of national researchers in farming system analysis, and students trained for MSC and Ph.D. degrees.

Two students take soil samples in experimental maize plots of a drip irrigation system. *Photo credit: Albert Barro.*

- **Activity 1:** Organize farmers field school on productivity-enhancing crop-livestock interventions and improved nutrition
- **Activity 2:** Organize training of trainers for FNGN and APESS on value chain development and sustainable intensification options, and for farmers
- **Activity 3:** Organize an annual meeting for sharing and validation of project research outputs with FNGN and APESS
- **Activity 4**: Organize training workshop on farming systems analysis
- **Activity 5** Organize training in experimental design and data analysis
- **Activity 6:** Supervise MSc and Ph.D. students

Result 4: Test the sustainable intensification assessment framework in alignment with project objectives and/or activities.

- **Activity 1:** Established an understanding of the importance of the SI Assessment Framework and how to use it in selecting context-specific indicators.
- **Activity 2:** Articulated operationalization of the SI assessment framework
- **Activity 3:** Finalized recommendation for the implementation and utilization of the SI assessment framework for research projects.

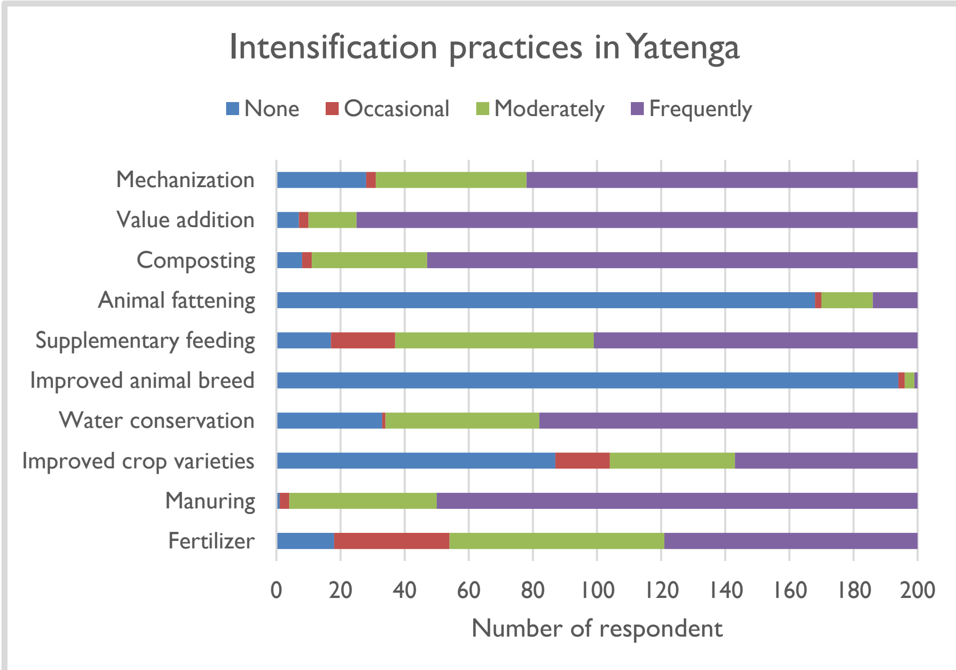
6. Accomplishments

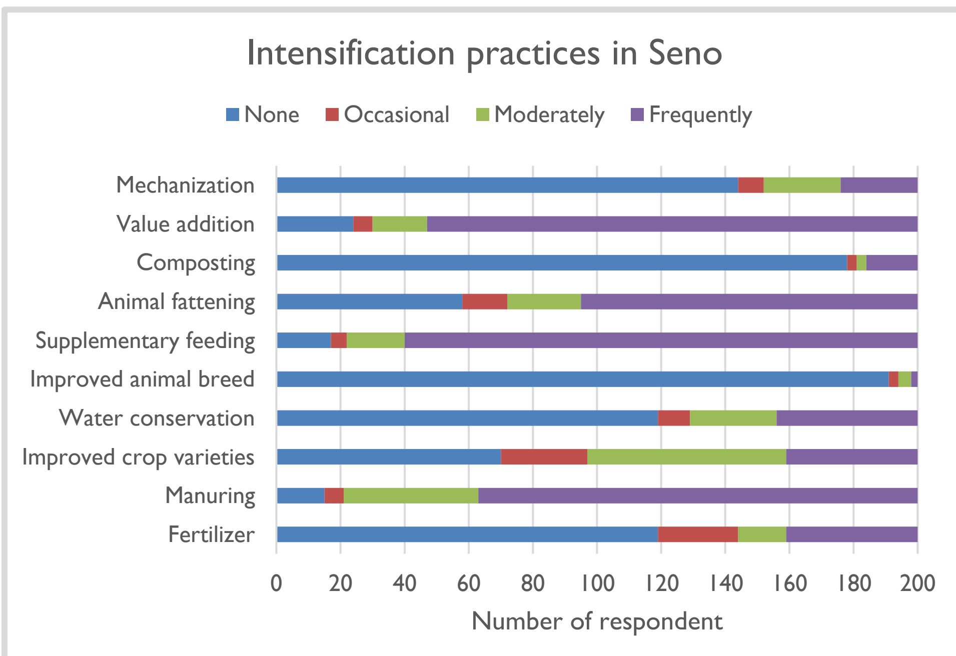
Baseline Characterization of Study Sites

50 households per community. Results of the frequency of key intensification practices in the project sites (n=200 in each project site) are similar in both sites except that extent of the practice of different intensification options tended to be influenced by the respondents' tradition (crop or livestock tradition). Yatenga people are farmers by tradition while Seno people are pastoralists.

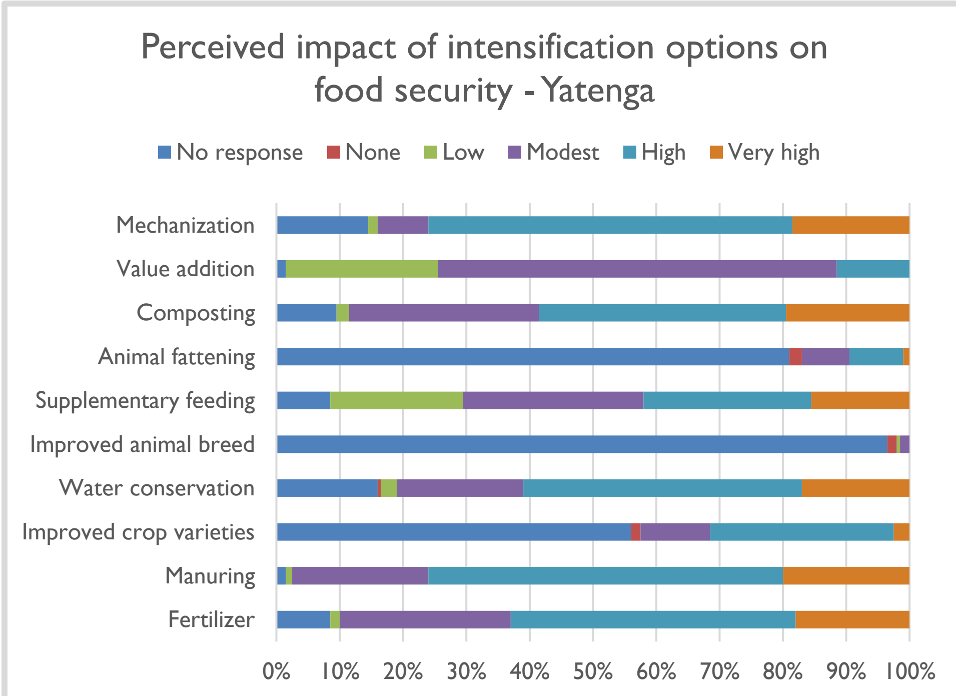
Variable	Yatenga (n=200)	Seno (n=200)
Average age of household head (year)	57.15±0.80[a]	49.85±0.89[b]
Number of years of residence (year)	47.78±0.95[a]	45.77±0.98[a]
Household size (number)	13.61±4.70[a]	10.35±5.40[b]
Land area cultivated by household (ha)	14.00±6.99[a]	4.67±4.39[b]
Livestock owned by household (TLU)	3.11±2.80[a]	5.42±3.60[b]
Total annual household revenue (USD)	1,009±14[a]	646±10[b]

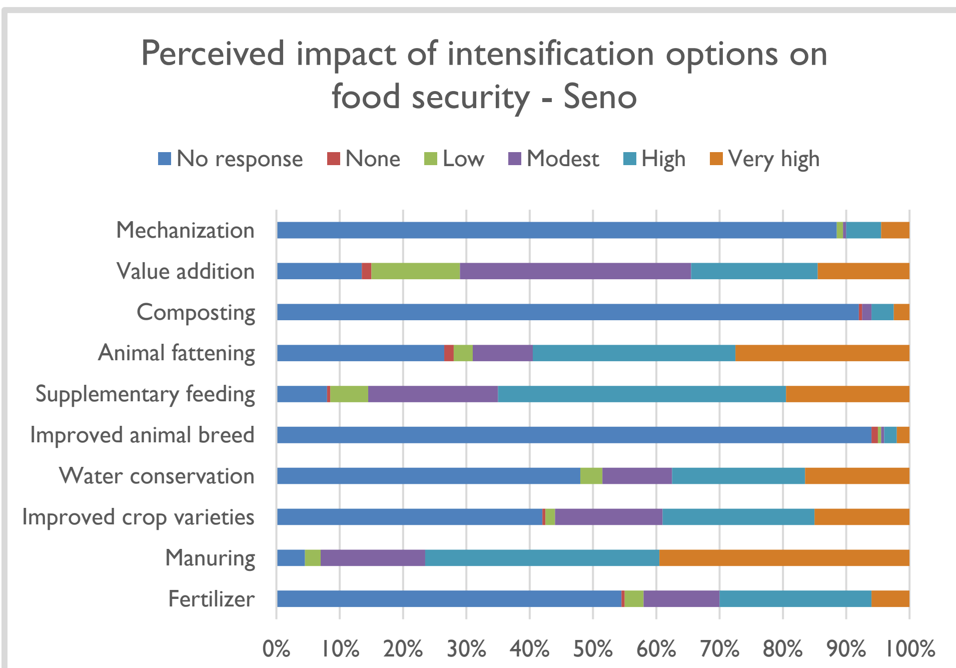
Table 1: Socio-economic features of surveyed households in the project sites





The intensification options were generally perceived to have a positive impact on food security in both project sites (n=200 in each project site, see the Figures below) although the degree of the perceived impact varied with each intensification option and site.





Review Opportunities and Constraints for Sustainable Intensification in the Sahel

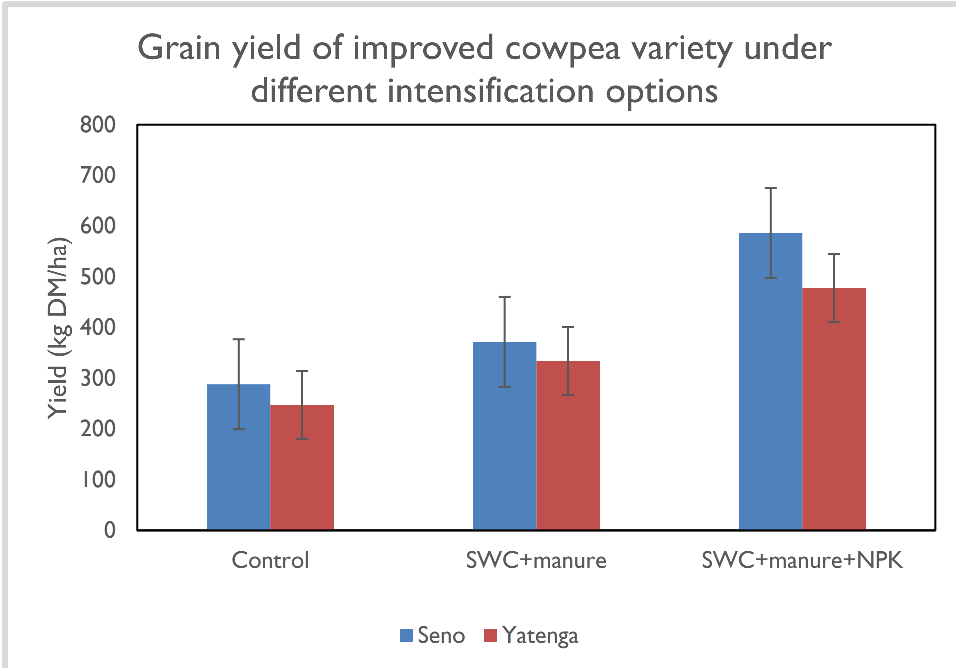
We reviewed the intensification options promoted by past projects and adopted or non-adopted by the smallholder farmers – strength, weakness, and potential for improvement. We identified various gaps in the past sustainable intensification intervention in the Sahel. We noted that the impacts (biophysical, socio-economic and environmental) of many intensification practices on the production systems and livelihoods of the smallholder farmers were not properly documented. This was because many of these sustainable intensification projects were not set out to measure its impact on household food security and nutrition in clear terms. This resulted in a weak link between sustainable intensification practices, and food and nutritional security. Our review revealed that there is a missing link on trade-offs and synergy when a combination of intensification practices was used as well as at various ladder of intensification. From the review, we suggested pathways to improve the existing sustainable intensification practices to move them from "best-bet" practices to "best-fit" practices. A combination of technical interventions best suited to specific farming systems and household categories, investments, and enabling policies and instruments will facilitate the adoption of sustainable intensification practices in the Sahel.

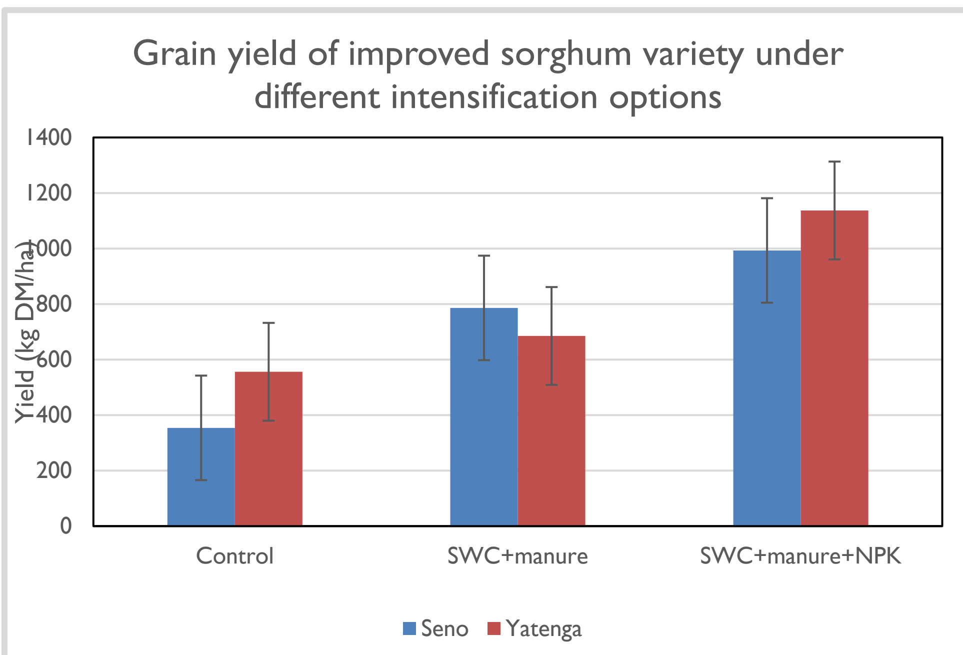
Agronomic Trials on the Effects of Intensification Options on Crop and Fodder Yields

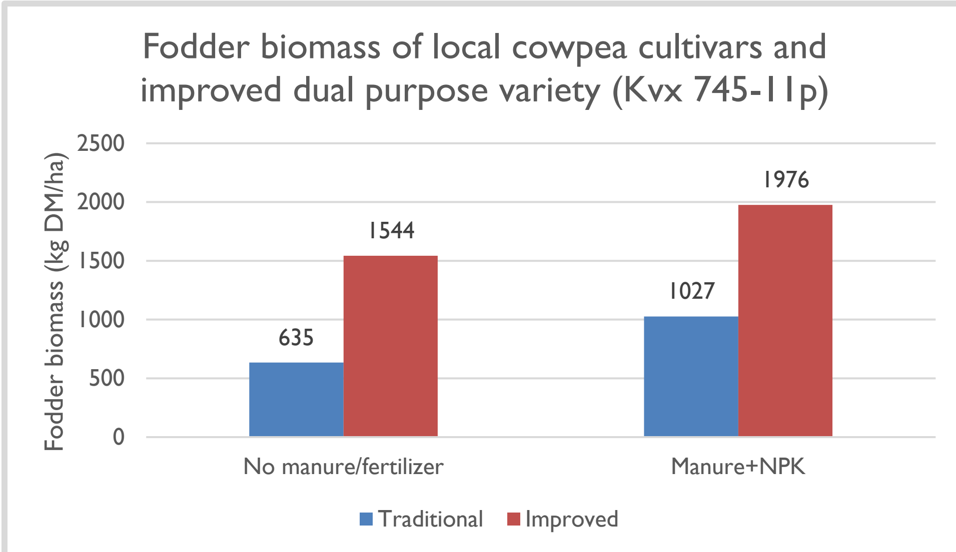
Over three cropping years (2016, 2017, 2018) – 12 farmers per community. Improved dual-purpose cowpea (KVX 745-11P) and sorghum (Sariaso 16) varieties were introduced into four project communities each in Seno and Yatenga provinces, Burkina Faso. The improved varieties produce more grains and more fodder for livestock.

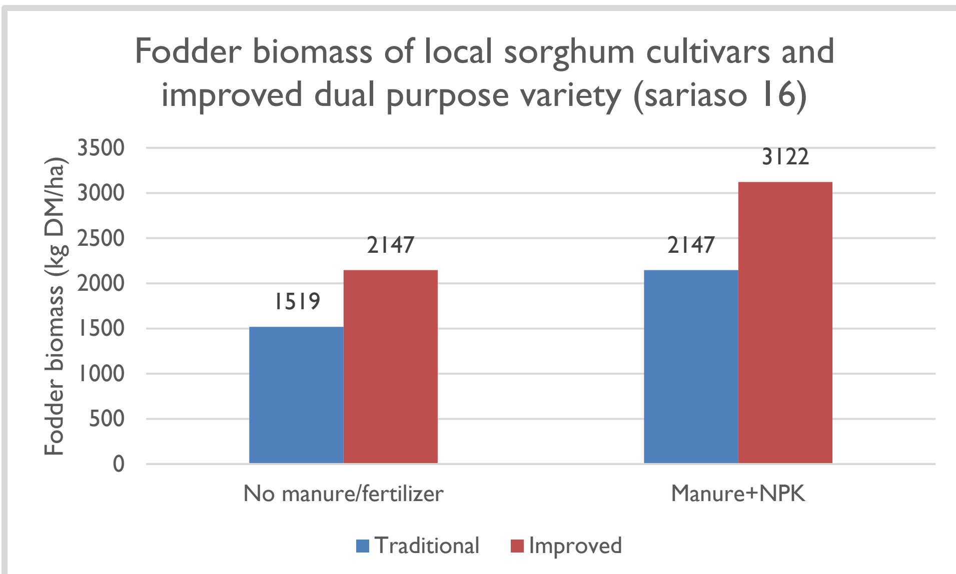
Picture of improved dual-purpose cowpea variety

Picture of improved dual-purpose sorghum variety


Grain yield of improved cowpea variety under different intensification options
Yield (kg DM/ha)
800
700
600
500
400
300
200
100
0
Control
SWC+manure
SWC+manure+NPK
Seno
Yatenga

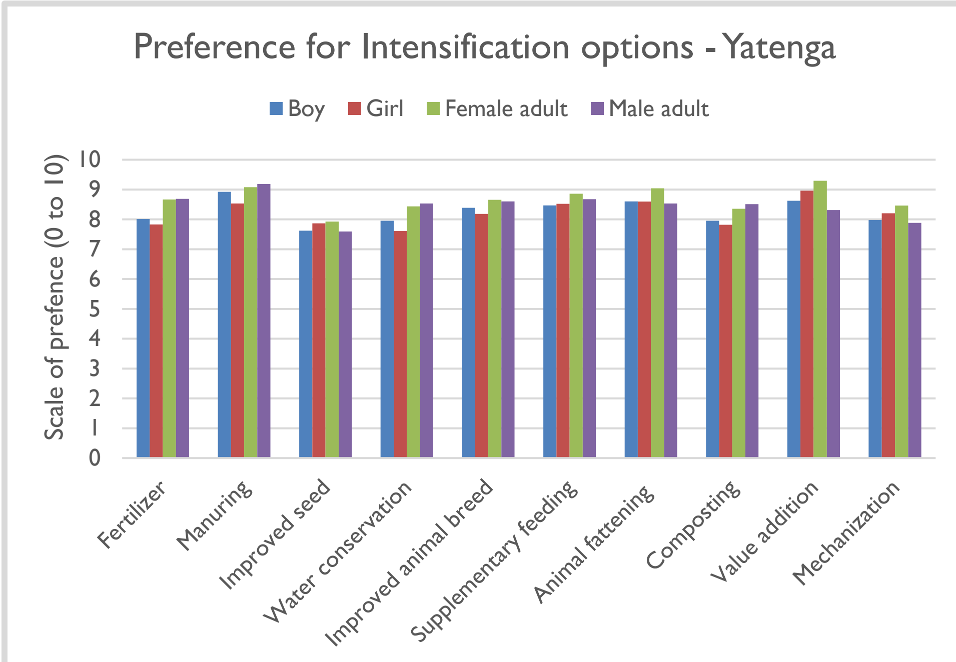

Grain yield of improved sorghum variety under different intensification options
Yield (kg DM/ha)
1400
1200
1000
800
600
400
200
0
Control
SWC+manure
SWC+manure+NPK
Seno
Yatenga

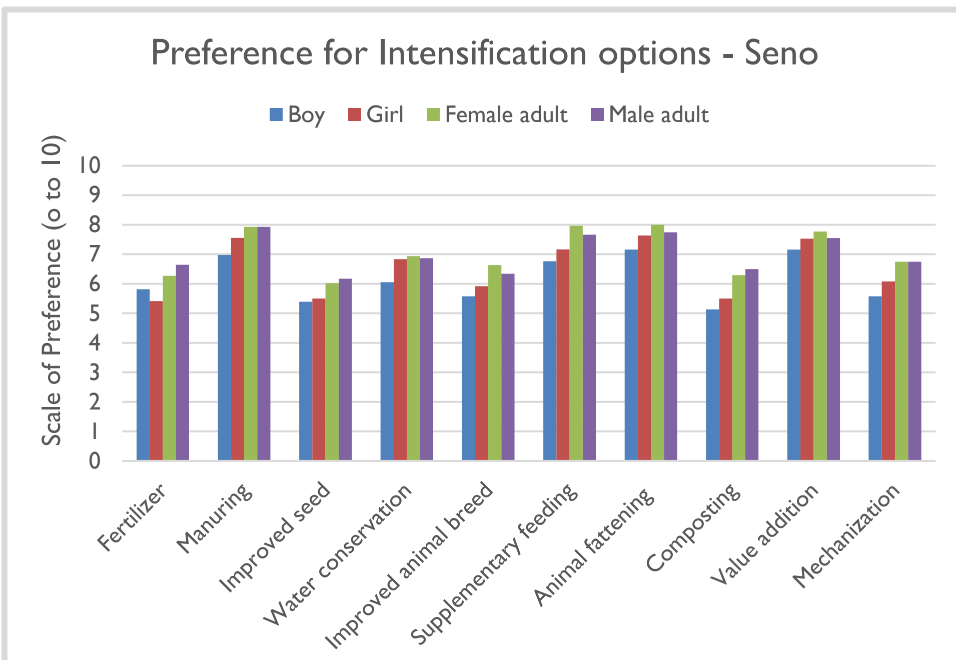




Survey on the Effect of Intensification on Gender 25 Households per Community with 4 Gender Groups (adult male, adult female, boy, and girl) per Household

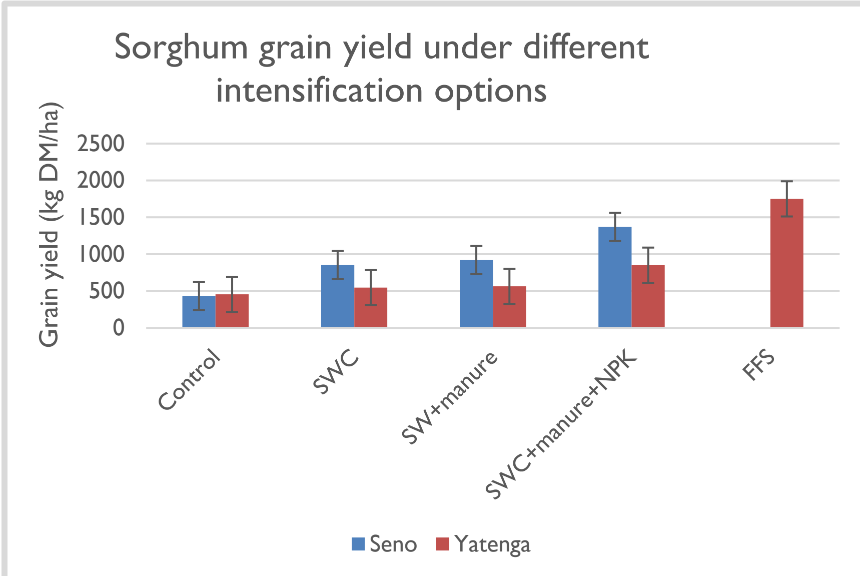
In this study on the effect of gender of intensification practices, we made a comparative analysis between men, women, young boys and girls in terms of technological choices and practices used for the intensification of crop and livestock production in these two provinces. The results showed a difference between the four gender groups considered in the study. The logistic regression showed that differences in the adoption of these technologies in the two study sites are related to the level of education, primary activity, household size, ethnic group, gender and age of respondents. Generally, there was a higher preference for intensification options in Yatenga province. Adult women and girls had a higher preference for supplementary animal feed, animal fattening, value addition and mechanization in both sites while adult men tended to prefer fertilizer application, manuring and water conservation.

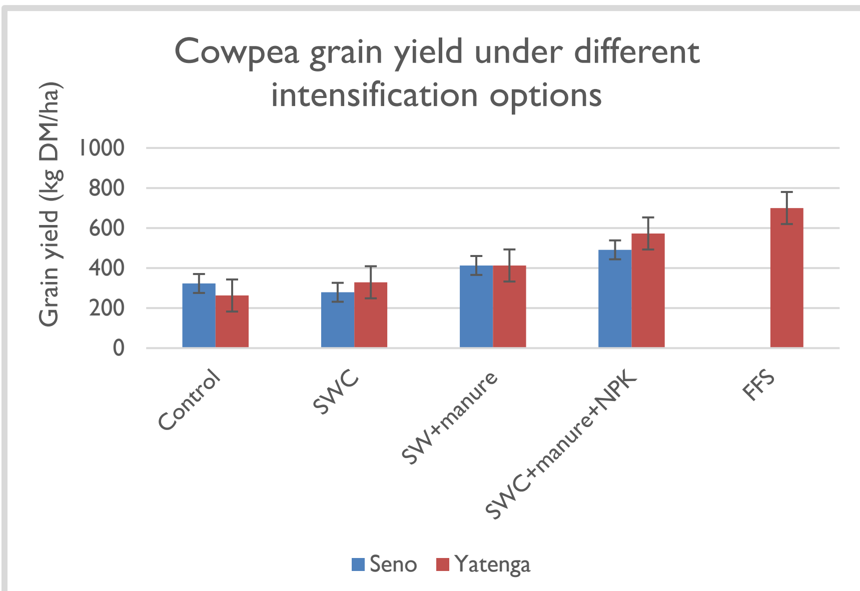




Establishment of Farmers' Field School (FFS) in Project Communities

Four farmers' field schools were established in each of the eight project communities. Each FFS is about 0.25 ha for improved cowpea variety and 0.25 ha also for improved sorghum variety. Each FFS consisted of between 10 to 20 farmers including women. Farmers' Field School provides a platform for knowledge exchange and learning by doing for the farmers and this can lead to better performance of technologies as in the case of higher yield of improved cowpea and sorghum varieties compared to the yields from the agronomic trials.



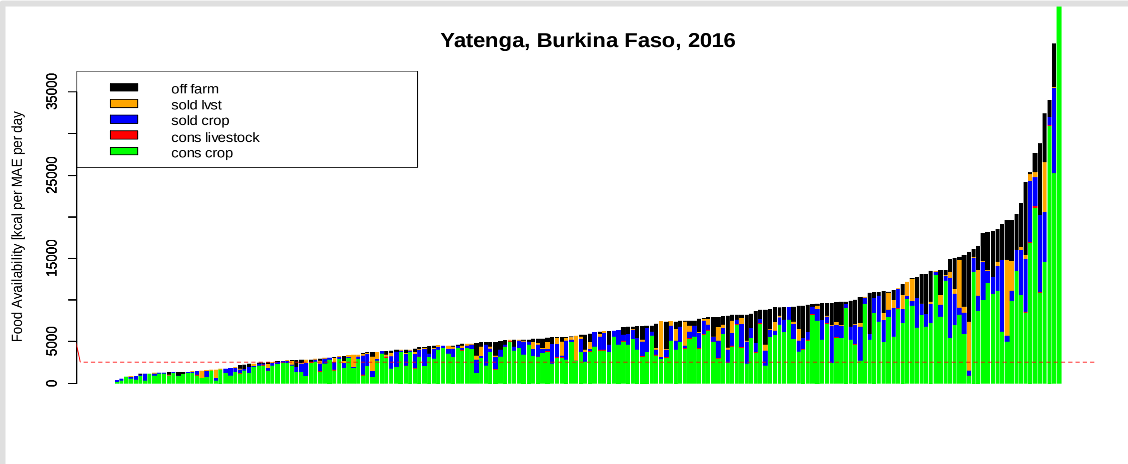


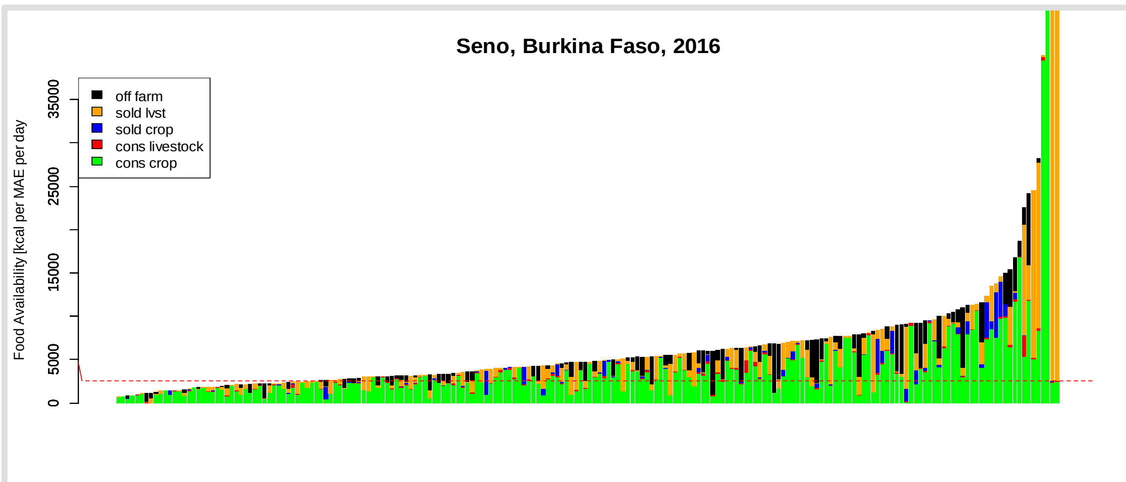
Monitoring of Household Nutrition (25 households per community) and Growth of Children Between 6 and 36 Months

The data collected by the Ph.D. student has been completed and the data is presently being analyzed.

Tradeoffs Analysis of Productivity Enhancing Intervention

To assess the trade-offs of productivity-enhancing interventions, four different intervention scenarios were evaluated: sorghum yields up by 50%, cowpea yield up by 50%, off-farm income increase by US$ 200 per year per family and goat production (milk and off-take) up by 50%. Results focused on the likely effects of the interventions on basic Potential Food Availability indicators. This work made use of data collected using an adapted version of the RHoMIS tool (Hammond et al., 2017a) that tries to capture a more integral picture of the well-being of farm households, with a special focus on food security.





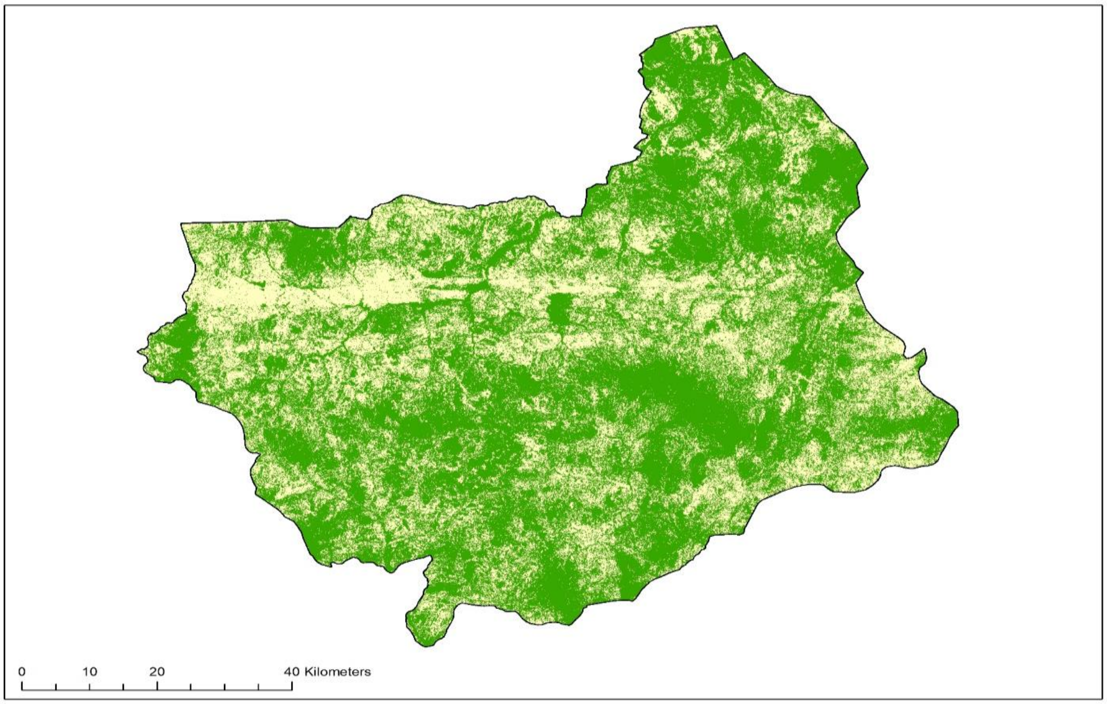
The figures showed the Potential Food Availability (PFA) results for Yatenga and Seno. On the x-axis 200 individual households are represented, ordered along with their PFA status (on the y-axis). In different colors, the contribution of crop consumption and sales, livestock product consumption and sales and off-farm income is shown.

Qualitative and Quantitative Assessment of Cost-Benefit Analysis of Productivity Enhancing Interventions Including Labor Productivity

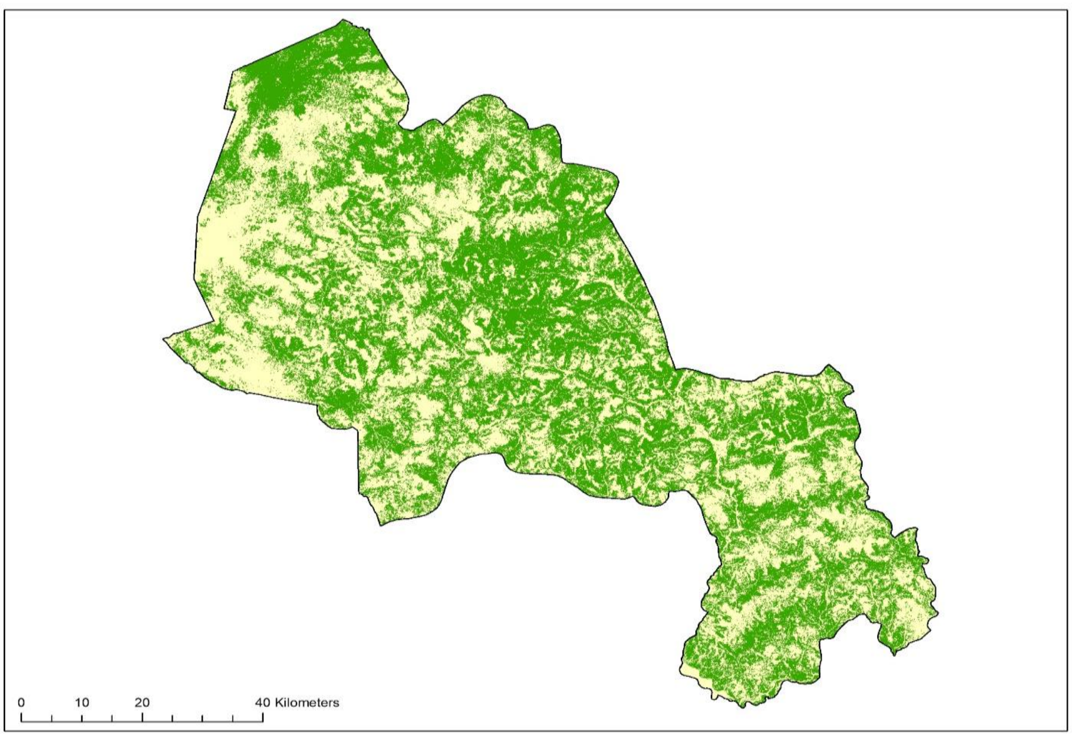
Two complementary approaches were used to understand the decision-making process of adoption of productivity improvement technologies and the cost and benefit were used. The first approach focused on the perception of the smallholder farmers on the cost and benefit of the productivity-enhancing interventions while the second approach was based on economic analysis (monetary and non-monetary costs and benefits: more efficient and cost-effective solutions).

Land-Use Patterns in the Project Sites

The results of land use patterns in Seno and Yatenga showed that 38% and 49% of the land is cultivated for crop production. Suggests that the pressure on land is higher in Yatenga than Seno.



Land use map for Seno site (cropland in yellow; rangeland in green)



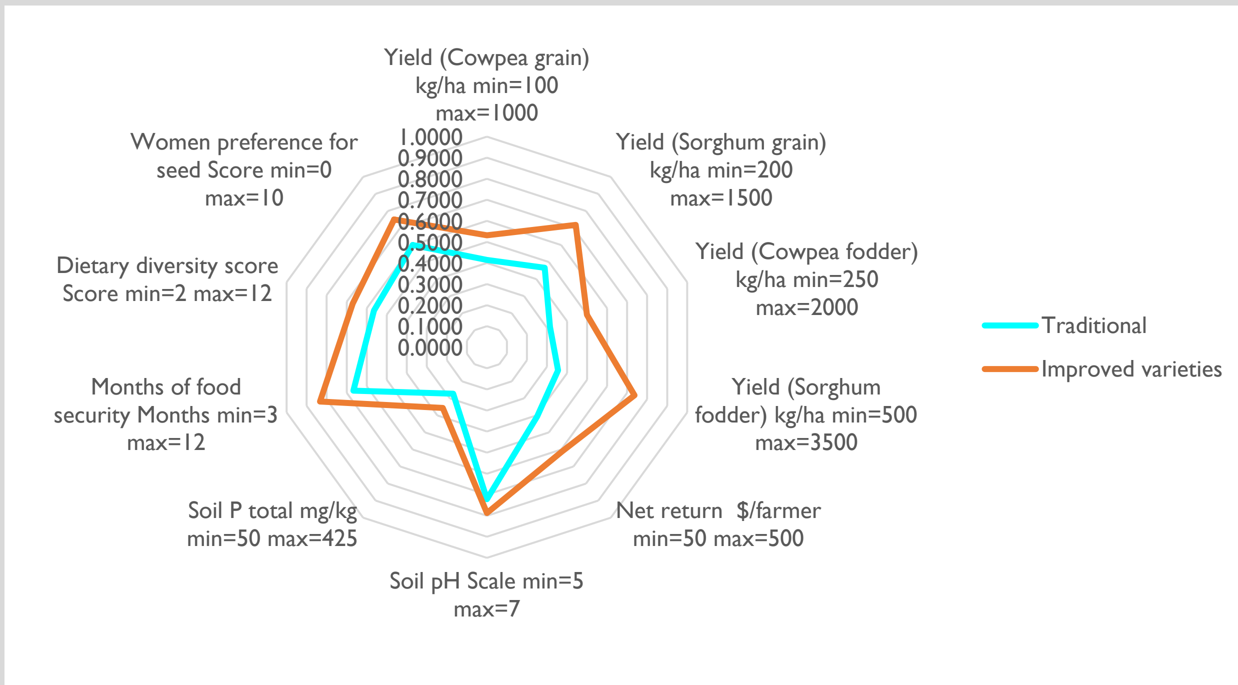
Land use map for Yatenga site (cropland in yellow; rangeland in green)

Table 2. The perceived benefit of productivity-enhancing technologies (% of respondents; n=25 in each site)

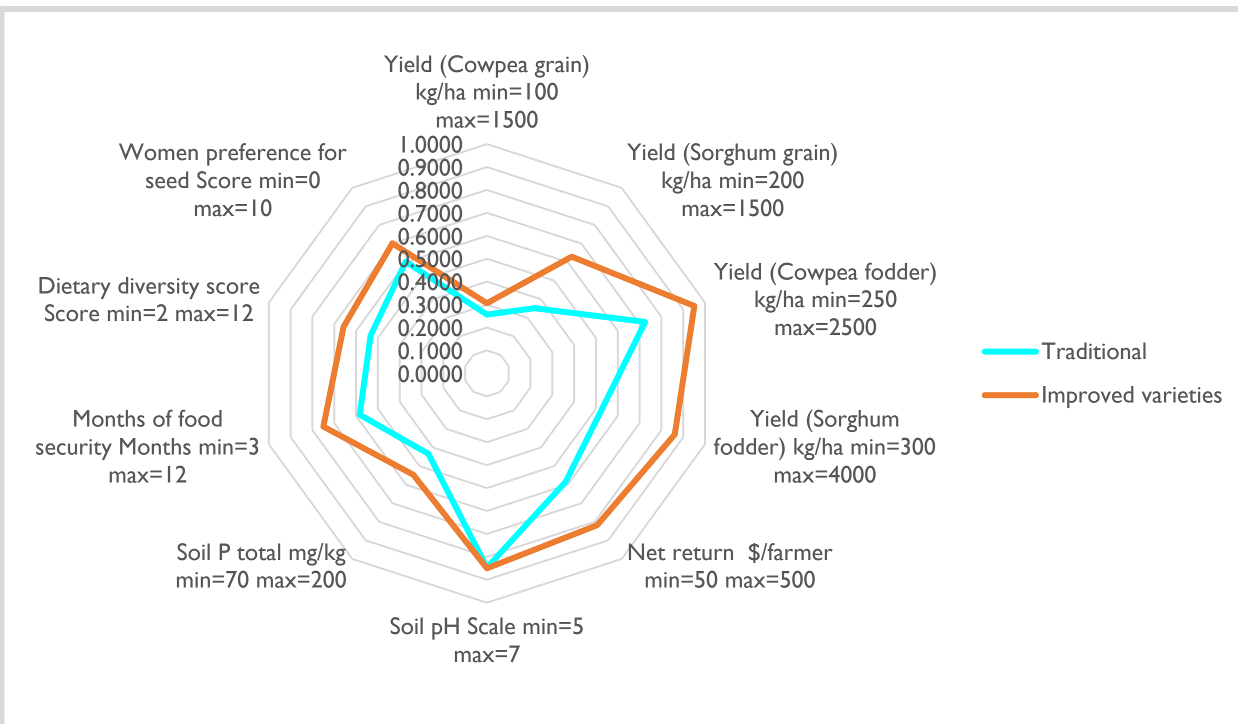
Technology	Yield increase		Soil fertility		Social benefit		Increased income	
	Seno	Yatenga	Seno	Yatenga	Seno	Yatenga	Seno	Yatenga
Improved variety	100	73	27	16	20	43	76	NI
Fertilizer	100	94	51	38	80	61	17	NI
Zaï	100	83	41	54	36	50	29	NI
Stone row	100	83	68	74	33	43	18	NI
Organic manure	100	98	59	75	26	42	14	NI
Cotton seed cake	100	81	NI	NI	11	33	81	43
Veterinary care	100	66	NI	NI	22	79	50	68

Implementation of Sustainable Intensification Assessment Framework

Introduction of improved dual-purpose cowpea and sorghum varieties impacted positively on productivity, economic and human domains of the SI assessment framework.



Radar chart of the introduction of dual-purpose cowpea and sorghum for Yatenga site



Radar chart of the introduction of dual-purpose cowpea and sorghum for Seno site

Capacity Building of Smallholder Farmers, Students and Young Researchers

Several trainings were conducted for smallholder farmers as well as for young researchers. The summary of the training is presented in Table 3 below.

Training Theme	Number trained		
	Male	Female	Total
Best nutrition practices (farmers)	88	416	504
Farmers' Field School (farmers)	234	67	301
Improved agronomic practices (farmers)	88	8	96
Sheep fattening (farmers)	20	12	32
Farming systems analysis (young researchers and students)	8	8	16
Fodder conservation techniques (farmers)	42	45	87
Experimental design and statistical analysis	7	8	15

Table 3: Summary of training conducted by the project

Six MSc students conducted their thesis research under the project while one Ph.D. carried out her thesis work under the project. She is currently drafting her Ph.D. thesis.

MSc students (all have completed their thesis):

Salifou Konfe - IDR, Université Nazi Boni, Bobo, Burkina Faso
Patrice Nikiema - IDR, Université Nazi Boni, Bobo, Burkina Faso
Aziz Simian - IDR, Université Nazi Boni, Bobo, Burkina Faso
Yolande Toe – IDR, Université Nazi Boni, Bobo, Burkina Faso
Arlette Toe - St Thomas d'Acquin University, Ouagadougou
Antoine Zorma - IDR, Université Nazi Boni, Bobo, Burkina Faso

Ph.D. Student:

Katian Napon - University of Ouagadougou, Burkina Faso

7. Utilization of Research Outputs

The dual-purpose cowpea and sorghum varieties introduced by the project are being planted by the farmers in the project sites. To build capacity in the production of seed of the improved varieties, farmers from the project sites were trained by INERA. Farmers' associations such as FNGN, APESS are scaling the improved dual-purpose cowpea and sorghum varieties.

The trainings on best child nutrition practices have influenced the dietary behavior of the population in the project sites, particularly in Yatenga. The dominant Mossi ethnic group in this site doesn't generally consume dairy products but throughout the trainings on the importance of animal source food for children under 5 years old, many women are now feeding milk and milk products to their children.

8. Future Challenges and Opportunities

The main challenge to project activities is the high-security risk in the project sites (Seno and Yatenga provinces) and the situation is not likely going to improve soon. From the project activities, many opportunities for future research include the following:

- Adoption studies of the uptake of improved dual-purpose cowpea and sorghum varieties by farmers, and in-depth assessment of economic and nutritional benefits
- Assessment of the effect of nutrition-sensitive livestock interventions on household food security and nutrition of children and reproductive women
- Tradeoffs analysis of productivity-enhancing interventions and their potential for cost-efficient scaling
- Analysis of the influence of community-level factors such as resource tenure institutions, leadership structures on intensification practices and household nutrition

9. Publications

Journal Articles

1. Ayantunde A.A., Duncan A.J., van Wijk M.T., and Thorne P. 2018. Review: Role of herbivores in sustainable agriculture in Sub-Saharan Africa. Animal 12:S2, s199–s209. DOI:10.1017/S175173111800174X.
2. Sanou S., Ayantunde A., and Nianogo A.J., 2018. Water and soil conservation techniques and food security in the northern region of Burkina Faso. African Journal of Agricultural Research 13(42): 2329-2342. DOI: 10.5897/AJAR2018.13454
3. Fraval S., Hammond J., Bogard J.R., Mary N., Jacob E., Mario H., Simon O., Imke B., Mats L., Nils T., Christine L., Todd R., Tim P., Bernard V., Paul D., David B., Pietro C., Paulin N., Chris O., Jannike W., Augustine A., Caroline B., Sabrina C., Esther K., James R., Tom S., Jonathan S., Clare Stirling., Viviane Y., and Mark W., 2019. Food access deficiencies in sub-Saharan Africa: prevalence and implications for agricultural interventions. Frontiers in Sustainable Food Systems. DOI: 10.3389/fsufs.2019.00104.
4. Kagambèga F.M., Bagagnan A.R., Ayantunde A., and Sawadogo L., 2019. Seasonal Effect on Growth Performance and Leaf Biomass Production of Two *Moringa oleifera Lam.* Varieties Grown under Sahelian Condition in Burkina Faso. Journal of Experimental Agriculture International 41(4): 1-12, 2019; Article no.JEAI.52432

Manuscripts under Review

1. Turner M.D., Eggen M., Teague M.S. and Ayantunde A. Variation in land access among villages in West Africa: A geospatial approach. Submitted to Land Use Policy
2. Napon K., Ayantunde A., and D.A. Dapola., E. Analyse selon le genre de la pratique des techniques d'intensification de la production agropastorale au Yatenga et au Séno (Burkina Faso). Submitted to Biotechnologie, Agronomie, Société et Environnement

Report

1. Mark W., Viviane Y., and Augustine A., 2018. Assessment of the potential food security benefits of increased income from crops, livestock and off-farm employment in Burkina Faso. International Livestock Research Institute, Nairobi, Kenya. Technical Report.

10. Datasets Produced

Dataset	Repository	Notes
SIIL Burkina Faso baseline survey	SIIL Dataverse	The baseline survey was conducted to characterize the crop-livestock systems in 8 project communities in two provinces of Burkina Faso (Seno and Yatenga) with focus on constraints and opportunities for intensification practices by smallholder farmers.
Farmers' perceptions of costs and benefits of productivity enhancing technologies in Sahelian zone of Burkina Faso	SIIL Dataverse-Unpublished	Surveys were conducted in 8 SIIL project communities in Seno and Yatenga provinces of Burkina Faso on costs and benefits of productivity-enhancing technologies. In each community, 25 farmers were interviewed. The objective of the study was to have a better understanding of the factors that can enhance the adoption of agricultural intensification technologies.
Survey of sheep fattening practices in Seno and Yatenga provinces of Burkina Faso	SIIL Dataverse-Unpublished	The data sets were from the survey on sheep fattening practices in Seno and Yatenga provinces of Burkina Faso. About a hundred smallholder crop and livestock farmers were interviewed in each province on their sheep fattening practices, experiences, costs and benefits.

ETHIOPIA

East Africa
Ethiopia

Sustainably Intensified Production Systems Impact on Nutrition (SIPSIN)

1. **Lead Institution:** Texas A&M University
   - U.S. Collaborating Institutions:
     - North Carolina Agricultural and Technical State University
     - Feed the Future Innovation Lab for Collaborative Research on Nutrition in Africa
     - Feed the Future Innovation Lab for Small Scale Irrigation
   - International Collaborating Institutions
     - International Water Management Institute (IWMI)
     - International Food Policy Research Institute (IFPRI)

2. **Research Team:**
   - Lead Investigator:
     - Neville Clarke, Texas A&M
   - Co-Investigators
     - Nicole Lefore, Texas A&M University
     - Seifu Admassu Tilahun, Bahir Dar University
     - Jean Claude Bizimana, Texas A&M University
     - Yihun Dile, Texas A&M University
     - Abeyou Worqlul, Texas A&M University
     - Michael Blummel, ILRI
     - Claudia Ringler, IFPRI

3. Executive Summary

The SIPSIN subaward from the Sustainable Intensification Innovation Laboratory (SIIL) studied the impact of several small scale irrigation schemes in Northern Ethiopia on household nutrition for participating families. The project involved collaboration between three Feed the Future Innovation Labs, three CGIAR International Research Centers and Bahir Dar University, a national university in Ethiopia. The SIPSIN project was directly linked with the Feed the Future Innovation Lab for Small Scale Irrigation (ILSSI) administered by Texas A&M AgriLife Research/Borlaug Institute for International Agriculture. The use of small scale irrigation in the dry season increased the quantity and variety of food produced, increased farm income, and resulted in improved family nutritional status by increasing both the quantity consumed and variety of diet. The environmental consequences were related to the increased use of groundwater and fertilizer and pesticide run-off. The Integrated Decision Support System (IDSS) was used to analyze field and household survey results to assess the effects of small scale irrigation on the production, environmental, economic and nutritional consequences of the farming systems studied. The IDSS outcomes were then used to interpret the impacts of ILSSI interventions in terms of the five domains of the SIIL Sustainability Intensification Assessment Framework (SIAF) and to express the results of

> The study showed that where there is geographic convergence of sufficient water, appropriate soils, and farm populations, using irrigation has major promise for increasing the sustainable production of food and improving food security and resilience in the total farming enterprise in Ethiopia.

the study in a comprehensive and holistic manner. Results were scaled to regional and national levels to assist decision-makers in planning and evaluating implementation local, regional, and national strategies for small scale irrigation.

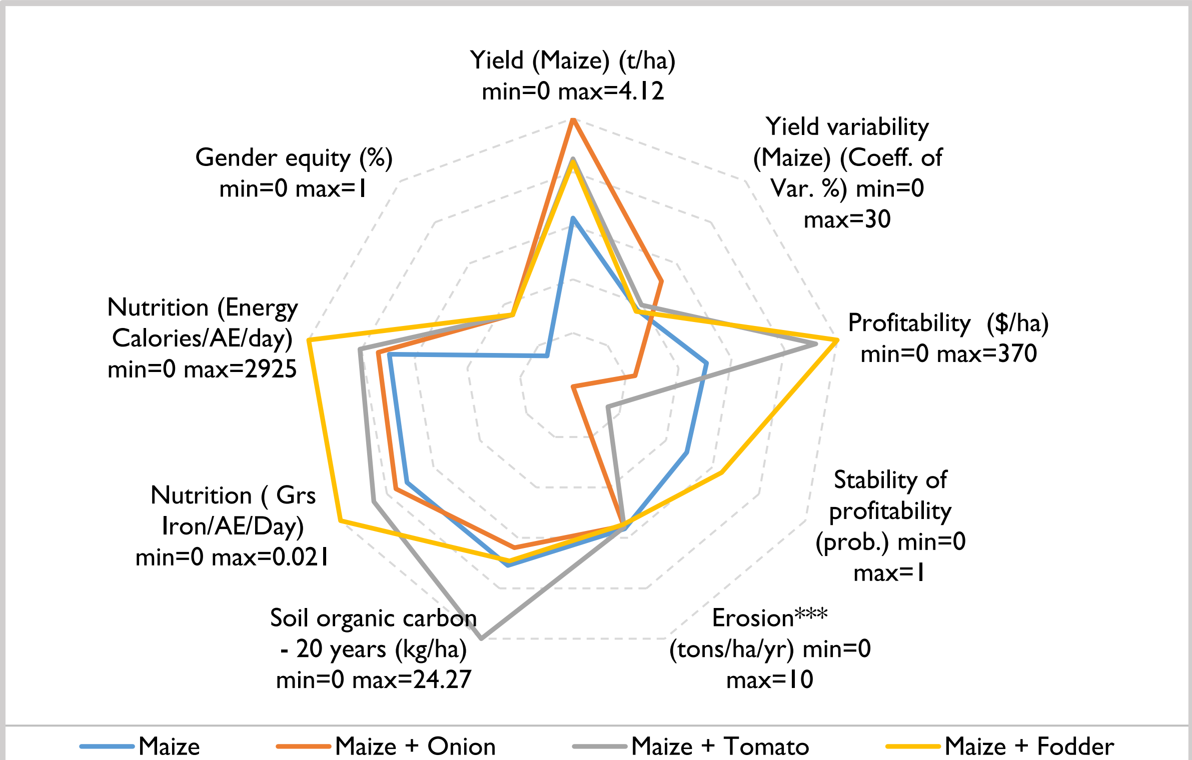


Figure 1. Evaluation of single cropped rainfed maize and multiple cropped rainfed maize with irrigated onion, tomato or fodder interventions across the five domains of sustainable intensification framework

4. Project Partners

- The Norman Borlaug Institute for International Agriculture, Texas A&M Agrilife Research, Texas A&M University System
- International Water Management Institute (IWMI)
- International Food Policy Research Institute (IFPRI) with Tufts University School of Medicine
- International Livestock Research Institute (ILRI)
- University of Illinois Appropriately Scaled Mechanized Interventions (ASMC) with North Carolina A&T University
- Bahir Dar University (BDU)
- Integrated Decision Support System (IDSS)

5. Project Goals and Objectives

Overall Goal

The approved annual operating plan for SIPSIN detailed the approach throughout the agreement, the institution/responsible persons and the planned impact stated concerning the relevant sustainable intensification indicator from SIIL and the key activities for implementation. Upon completion of the SIPSIN project, all major tasks were successfully completed. In summary, the SIPSIN operational plan included:

Overall Objectives

The overall objective of SIPSIN was to determine the interaction between the use of sustainably intensified production systems and the status of family nutrition and health in participating households in Ethiopia.

Farmer training in Bahir Dar, Dangila, Dangishita, Ethiopia. Photo credit: ASMC-BiT.

Objective 1: Conduct field studies that provided more detailed and comprehensive data on production, environmental and economic results used in combination with selected ILSSI products.

Objective 2: Conduct household surveys that extended the number of ILSSI surveys of participating households and control groups with augmented questions on household and, more specifically, femail and children diets, nutritional security and health.

Objective 3: Integrated modeling using the IDSS with the main focus on Texas A&M studies with collaboration and parallel analyses done by BDU, North Carolina A&T University and IWMI.

Objective 4: Capacity development involving at multiple levels of scale.

Objective 5: Application of the IDSS to the use of the SIIL SIAF to provide an integrated visualization of the multiple outcomes of SIPSIN.

6. Overview of Activities

The use of irrigation, especially in the dry season, was a central component of the multiple farming systems that were studied in this project. SIPSIN field studies built on related activities of the ILSSI with increased emphasis on establishing and evaluating broader farming system approaches in farmers' fields. Additional SIPSIN farm-level studies were completed for the fodder-livestock and environmental systems components. The production, environmental and economic results of farming system studies completed by ASMC in 50 households for other purposes added substantially to the results of SIPSIN and demonstrated the merits of the conservation tillage system in these circumstances. The environmental assessments undertaken by IWMI included environmental sampling related to regional cropping systems other than those under the SIPSIN study. The results of these studies were shared with appropriate local and regional governmental authorities, especially in the instances where the levels of chemical residues were greater than WHO standards. Due to illness of the Tufts principal investigator, the baseline and end-line household surveys of status of family nutrition were done by IFPRI (rather than jointly, as planned) using a local consultant. BDU conducted training sessions at the outset of the agreement on the importance of nutrition for women in the participating farm studies.

BDU faculty and graduate students were actively involved in experimental design, communication with participating farmers and first-level data acquisition. By having a single focal point at BDU for the collection of data across the multiple segments of the SIPSIN field studies, and with ongoing engagement between BDU and the IDSS team, data were consistent and could be confidently aggregated for analysis using the Agriculture Environment/Policy eXtender (APEX) and Farm Scale Nutrition and Economic Simulation

As shown elsewhere, students were able to use this experience and the resulting data in their graduate theses. BDU had responsibility for collecting and first-level analysis of data from the ASMC studies. ASMC in their separate studies of hand tools for women farmers also used BDU for field studies, further enhancing the continuity of data across projects.

Model (FARMSIM) models in the IDSS. North Carolina AT&T graduate students were also active in data acquisition and analysis with a resulting Ph.D. dissertation emanating from this work.

The IDSS team conducted multiple workshops (sponsored by ILSSI) throughout the SIPSIN agreement, and mentored and served on the graduate committees of Masters and Ph.D. students that used the SIPSIN experience and data for their theses. Because two of the first line IDSS scientists were Ethiopians with advanced degrees from Northern universities, the communication across the multiple elements of the SIPSIN was highly effective.

Using data from the field and household surveys, and building on and extending the IDSS modeling methodologies, the analysis and interpretation of results were completed as planned. The IDSS team conducted a comprehensive analysis to show how the IDSS modeling methodology was used to populate the SIIL SIAF with quantitative results. It was proposed that the IDSS could be readily adapted for other studies, including the development of a web-based system for broader application. In this final report, the product of the IDSS as expressed in the SIAF radar charts is used to show the integrated and interactive results of the SIPSIN study across the five domains of the SIAF.

7. Accomplishments

IFPRI collected and analyzed three rounds of household survey data in 2017 and 2018 with 368 households in Bahir Dar Zuria and Dangila districts of the Amhara Region. The aim was to draw broad linkages between water and nutrition. The SIPSIN project enabled the expansion of the ILSSI household surveys to include a quantitative nutrition module, malaria rapid diagnostic test, and an anemia/hemoglobin test in the surveys. The results of the SIPSIN analysis are published in an IFPRI discussion paper entitled, "Irrigation and women's diet in Ethiopia: a longitudinal study." The study showed that irrigators are more likely to meet the minimum dietary diversity for women (MDDW), have higher energy and calcium intake, and lower prevalence of anemia, than women from non-irrigating households. The preliminary findings suggest that there is high seasonal variation in women's diets, but this can be partly offset by irrigation practices. Results were shared with stakeholders in Ethiopia, such as the Ethiopian Public Health Institute and the upcoming National Nutrition Conference (December 2019), as well as the USAID Mission, Stockholm World Water Week, and a seminar in Washington, DC. The results will be published in a peer-reviewed journal article and policy note.

> The results to date suggest that the first cut of vetch could be used for soil improvement practices, while two additional cuts could be used as forage well into subsequent months.

IWMI partnered with BDU under SIPSIN, to assess the effect of agrochemical usage in watersheds on the surface and shallow groundwater quality comparing two watersheds (Robit Bata, Dangishta) with different irrigation intensities. The study collected unique datasets for ground and surface water, as well as household data on water sources, uses and quality indicators. Results show the importance of understanding the main transport mechanisms for agro-chemicals in a watershed (groundwater or surface run-off), in addition to the number of agrochemicals used. In areas where intensification is greater, higher concentrations of agrochemicals in water bodies extended to the dry months. In some sites, concentrations of endosulfan α & β (associated with khat) and Profenofos (associated rainfed maize) exceeded WHO guidelines in wells across seasons. In short, results confirmed a causal relationship between the agricultural intensification, the dominating hydrological process and the use of agro-chemicals in functions of the landscape. The occurrence of pesticide levels followed a pattern with irrigation activities as well as usage for specific agricultural production systems, including livestock. The monitoring of Lake Tana also suggested the impact on water bodies downstream. IWMI undertook continuous stakeholder engagement to share research-based evidence throughout the project period, particularly related to agro-chemical risks to human and livestock health, and the environment. Regional authorities committed to more monitoring of agrochemical stores in the region, to undertake farmer trainings, and to follow up on guidelines and regulatory systems.

ILRI utilized funding through the SIPSIN project to expand studies from ILSSI related to irrigated forages, particularly in the Bahir Dar Zuria district of the Amhara region. SIPSIN enabled ILRI to follow up on the spread of irrigated forages in selected sites, which had two components: adopters allocated more land to irrigated forages and new farmers adopted irrigated forages. At the field level, ILRI also integrated forages into conservation agriculture (CA) in alignment with the activities of BDU and SIIL. Unfortunately, the irrigation pumps did not arrive in time for the dry season, which delayed field studies. Forages were grown, harvested and then used as mulch on trial areas; ILRI supplied the planting material and provided technical support. Maize yield was not affected by management practices, however, vetch outperformed lablab.

The field and survey studies completed by multiple SIPSIN partners were part of an integrated plan to assess the impact of sustainably intensified production systems on family nutrition. Data and first-level analysis from these studies were analyzed using the IDSS. The SIIL SIAF identifies five major performance domains; the use of radar charts provides a way of showing the results of the SIPSIN studies so that the performance domains may be seen on one graphic display. The IDSS was used to analyze and organize the SIPSIN data under the five SIAF domains. The SIPSIN team chose to display selected summaries of the SIPSIN accomplishments using radar charts to show the integrated summary of results under the SIAF domains.

Application Of The IDSS To The Use Of The SIIL SIAF

The SIAF focuses on evaluating the intertwined impact of smallholder agricultural management intervention on productivity, environmental sustainability, economic viability, human conditions, and social equity. Assessing these central issues through the SIAF contributes knowledge and informs policy to achieve the USAID Sustainable Development Goals (SDGs, Nilsson et al. 2016, Sachs 2012). The IDSS analysis addressed the five domains of SIAF as follows:

Production: The IDSS evaluated the production and production stability of a farming system in terms of the yield and yield variance. The impact of different agriculture water and other resource management was evaluated by comparing the crop yield of the corresponding management interventions.

Environmental sustainability: The environmental indicators of different management interventions were evaluated using calibrated and validated biophysical simulation models. The calibrated biophysical models were simulated using historical climate data (1997 - 2017), which enabled estimating the environmental sustainability indicators such as soil loss and soil organic carbon.

Economic: The IDSS used profitability and profit stability as SIAF economic indicators. The economic value of several agricultural management interventions was evaluated against these economic indicators and the most profitable and environmentally sustainable interventions were identified.

Human and Social: The IDSS evaluated the SIAF's human and social domain through nutritional value and gender equality perspective. The nutrition indicators evaluated were calories, protein, fat, calcium, iron, and vitamin A. The nutrition outcome of the management interventions were evaluated using the FARMSIM model. The social aspects of sustainable intensification were evaluated through gender equality by comparing the labor time requirements of the management interventions for men and women. The Women Empowerment in Agriculture Index (WEAI), a survey-based tool of IFPRI, was also used to study women's empowerment and inclusiveness of the interventions.

The conceptual framework of the evaluation of the sustainability intensification practices is presented in Figure 2. The three field experimental designs 1) conservation agriculture and its family, 2) multiple cropping, and 3) irrigation application rates were evaluated in terms of the five domains of sustainability using the IDSS.

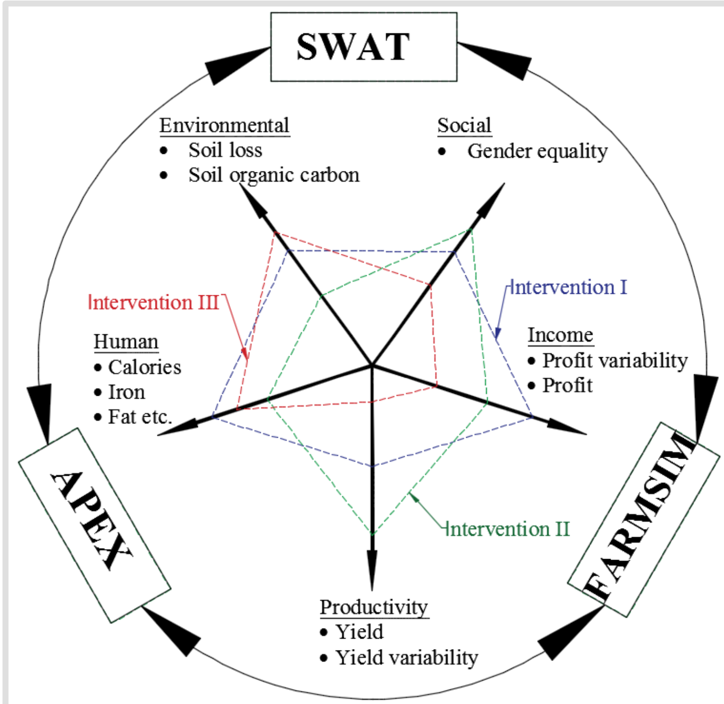


Figure 2. Conceptual framework to evaluate sustainable intensification of agricultural management interventions.

Multiple Cropped Maize With Irrigated Vegetables And Fodder

Multiple cropping of maize cultivated after irrigated and fertilized vegetables or fodders increased maize yield substantially compared to baseline conditions. This is attributed to the improvement in soil fertility due to residual nutrients from dry season cropping (i.e. vegetables or fodder). However, the highest and most consistently stable maize yield was observed when it was planted after onion and fodder, respectively.

The highest profit was observed under rainfed maize + irrigated fodder interventions (98% higher than the single cropped maize). A reduction in profit was observed under rainfed maize + irrigated onion interventions when compared to single cropped maize (53% lower profit than single cropped maize) due to the higher cost of production of onion.

Under the environmental domain, there was no significant difference in soil loss among the multiple cropped maize. However, the crop residues of rainfed maize + irrigated tomato replenished the soil organic matter substantially compared to other interventions.

The use of irrigation during the dry season to expand cropping produced additional food and generated income. The increased income as a result of irrigated crop sales, especially fodder and tomatoes, allows the household to purchase additional food items such as animal products (milk, eggs, beef, and chicken) from the markets to complement their nutrition.

Production and sale of fodder increased the availability of animal feeds at the market. Feeding fodder to animals is vital to increasing dairy and meat product availability which subsequently improves the availability of calcium, iron, calories, fat, and protein to households.

The gender equity and women empowerment analysis, which was based on IFPRI surveys, suggested that women in Ethiopia performed better in terms of their input in decisions about irrigated cash crop farming after interventions than before the intervention. Also in this study, a comparison of the number of hours allocated by women to different agricultural activities before and after the introduction of small-scale irrigation technologies shows an increase in the number of hours worked after the interventions. However, more research is needed to draw definite conclusions on the gender-related aspects. The IDSS evaluation of multiple cropped maize with irrigated vegetables and fodder are systematically summarized in a radar chart in Figure 3.

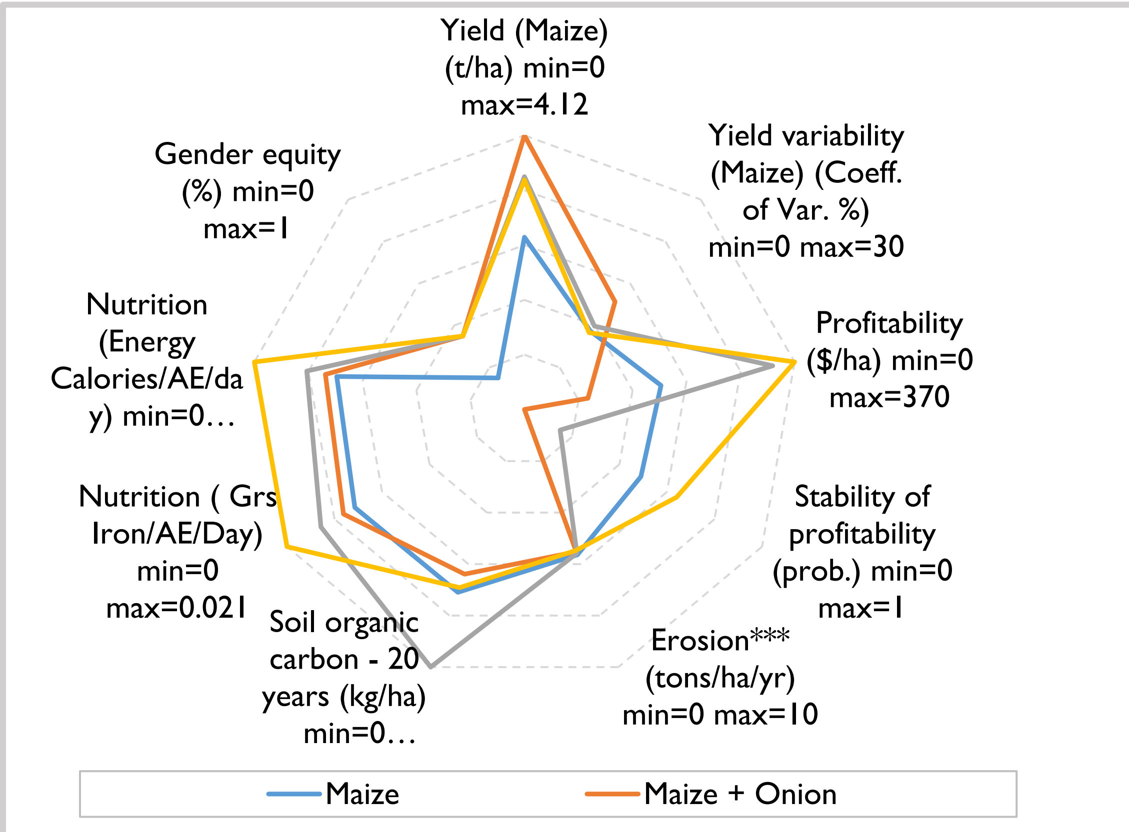


Figure 3: Evaluation of single cropped rainfed maize and multiple cropped rainfed maize with irrigated onion, tomato or fodder interventions across the five domains of sustainable intensification framework.

Multiple Cropped Teff With Irrigated Vegetables And Fodder

Like the multiple cropped maize with irrigated vegetables and fodder, multiple cropped teff with irrigated vegetable or fodder provided promising outcomes in terms of the five domains of SIAF.

Multiple cropping of rainfed teff cultivated after irrigated and fertilized vegetables or fodders increased the rainfed teff yield by 15% compared to baseline condition due to improved soil fertility as a result of residual nutrients (nitrogen) from the dry season irrigated crops. No difference in teff yield and yield variability was observed when teff was cultivated in multiple cropping systems.

The highest profits were observed when teff was multiple cropped with tomato and onion; however, the profit under teff plus onion was highly variable, probably due to higher yield variability.

Under the environmental domain, there was no significant difference in soil loss between the single and multiple cropped maize. However, the crop residues resulting from multiple cropped tomato replenished the soil organic matter.

The use of irrigation during the dry season produced additional food and generated more income. Higher-income was generated with multiple cropping teff and vegetables rather than maize and vegetables, which increased the potential for households to purchase supplemental food items to supplement their nutrition. Also, the production and sale of fodder increased the availability of animal feed at the market. Adding fodder to diets of animals can increase meat and dairy product availability which thereby improves the availability of iron, vitamin-A, fat, calcium, and protein to households.

Gender equity and women's empowerment were evaluated based on IFPRI's protocols and surveys. The results suggested that women in Ethiopia did better in terms of decision making on agriculture production, access to technology, control over income and time use after the irrigation interventions than before the interventions. Direct counting of women's labor time showed that the number of hours worked for certain agricultural activities reduced substantially with the introduction of small scale irrigation technologies. More research is needed, however, to draw definitive conclusions.

The IDSS evaluation of multiple cropped teff with irrigated vegetables and fodder are systematically summarized in a radar chart in Figure 4.

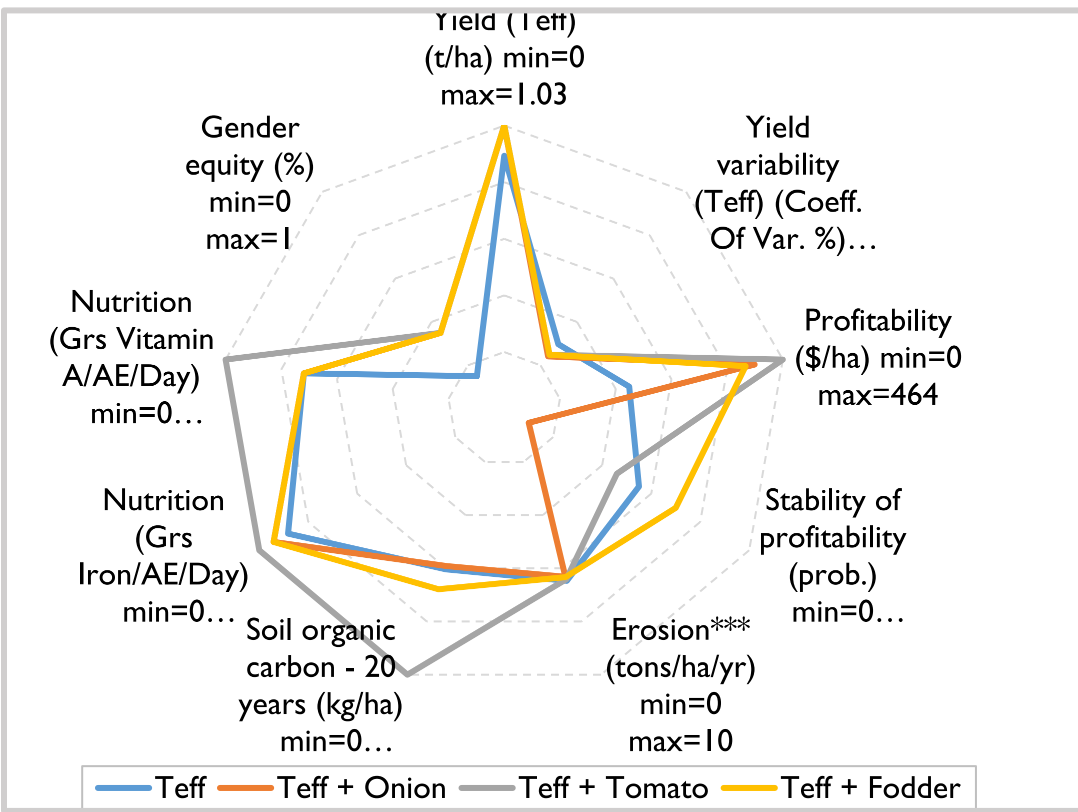


Figure 4: Evaluation of single cropped rainfed teff, and multiple cropped rainfed teff with irrigated onion, tomato and fodder practices across the five domains of sustainable intensification framework.

Evaluation Of Water Application Efficiencies Of Vegetable Production

The tomato yield and water stress days for different irrigation amounts (i.e. 100 mm to 850 mm) over the 22 years simulation period are presented in Figure 5. When the tomato was cultivated with 100 mm of water, there was substantial water stress of up to 27 stress days. When the irrigation amount was increased to 250 mm, the number of water-stressed days decreased to 8, and the yield increased by 47%. However, after an irrigation amount of 400 mm application, the yield did not significantly increase (p-value > 0.05). Thus, the irrigation-production function (Figure 5) indicated that the highest tomato yield was obtained when 400 mm of water was applied as irrigation.

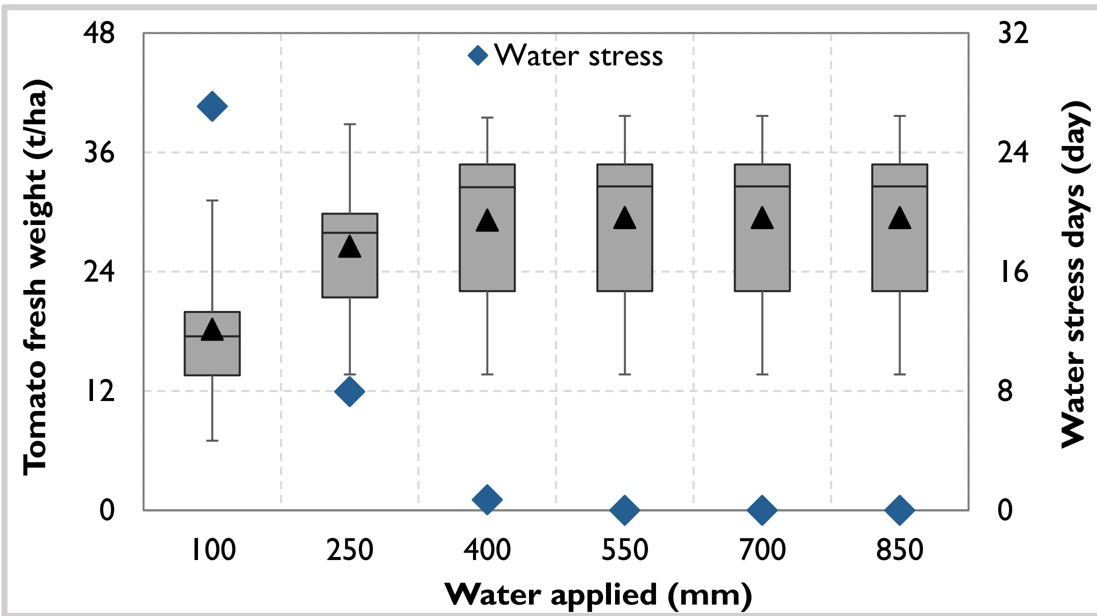


Figure 5. Boxplot representing 22-year (1995 to 2016) simulated tomato yield for a different amount of irrigation water application (i.e. 100 mm to 850 mm). The rectangular boxes represent the first and the third quartile of tomato yield; the median yield is represented by a segment inside the rectangle; average yield is represented by the triangles, and the whiskers above and below represent the minimum and maximum tomato yield.

The evaluation of the water application rates in terms of the five domains of the SIAF indicated that the highest outcomes would be achieved at irrigation amounts of 400 mm. The major outcomes of irrigation application on tomato are:

- The highest tomato yield and aboveground biomass were obtained after a 400 mm irrigation water application, which also provided the highest aboveground biomass. The residual biomass increased the soil carbon and modified the biological and physicochemical characteristics of the soil;
- Irrigation water application at 100 mm provided the lowest tomato yield with the highest yield variability;
- Irrigation beyond 400 mm of water may provide a similar yield as that of the 400 mm irrigation; however, irrigation beyond 400 mm of water is not a preferred water management option since it requires more labor for irrigation. Moreover, such water application practices increased soil erosion;
- The nutrition outcome of a 400 mm irrigation application is the most profitable since it provides more yield and also requires less labor as compared to irrigation application beyond

400 mm. Moreover, the 400 mm irrigation water application fulfilled household nutrition requirements except for fat and calcium. This is a general observation for households in Ethiopia and may also be due to the type of diet consumed. The gaps can be closed through crop production and food consumption diversification, especially the consumption of animal products;

- Since women heavily participate in irrigation activities, irrigation practices beyond 400 mm may take more labor time from women at the cost of other household and agricultural activities.

The integrated outcome of water use efficiency of tomato across the five domains of the SIAF is summarized in the radar chart in Figure 6.

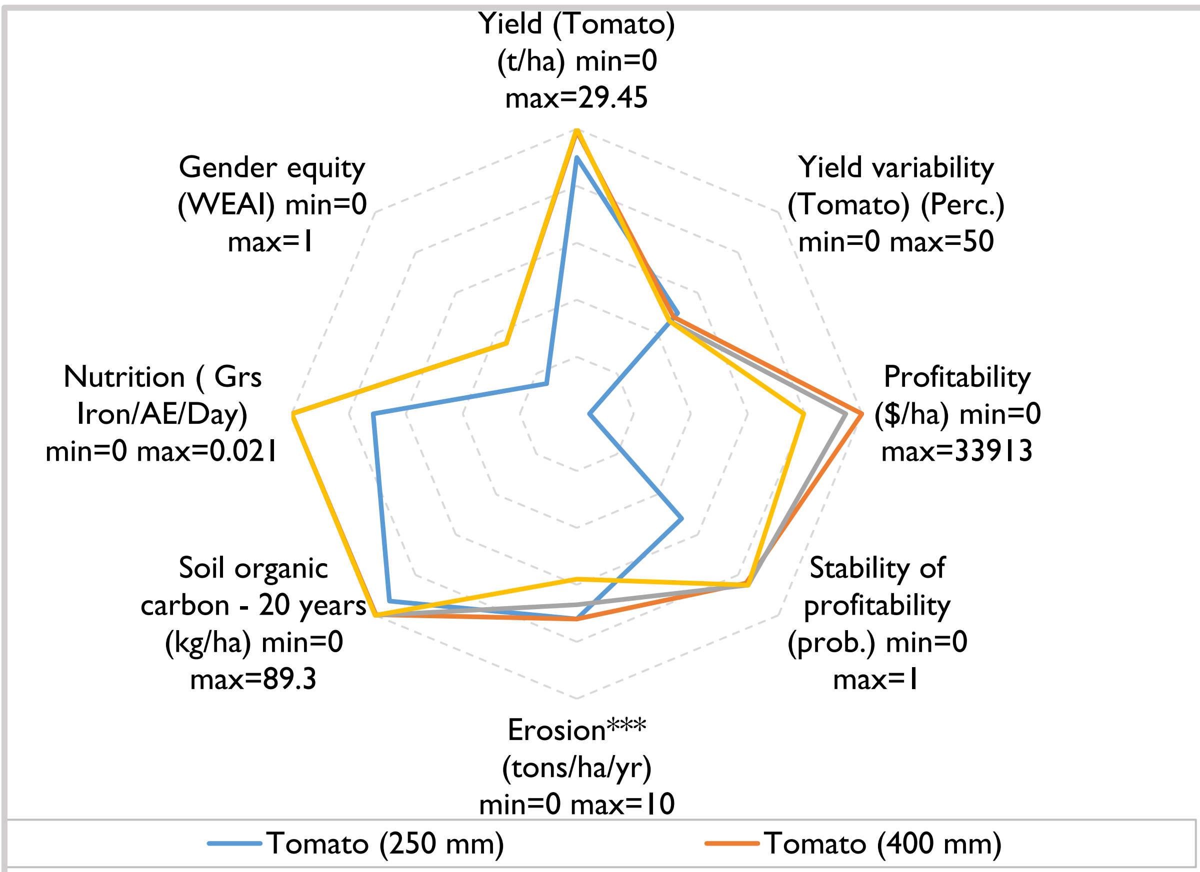


Figure 6: Evaluation of water application practices examined in terms of the five sustainable intensification framework domains

Capacity Development

With the close partnership/collaboration between ILSSI and SIIL on the SIPSIN project, Texas A&M covered the expenses and reported the SIPSIN related travel and IDSS capacity building for the partnership under ILSSI. Individual partners conducting field studies had focused on local training and education activities. The main effort relevant to SIPSIN was the ongoing training and capacity building related to the IDSS. Sub-awardees also engaged graduate students in field studies as long-term training toward degree fulfillment, particularly thesis papers and subsequent publications. The list of publications and theses shown in Appendix I clearly shows that there has been active and ongoing engagement with national partners at the university, government and private sector.

SIPSIN STUDENTS

Name	Gender	University	Degree	Major or subject	Degree completion date	Status
Feleke Kuraz	M	BDU	Ph.D.	Water Resources Management and Engineering		Ongoing
Sisay Asres	M	BDU	Ph.D.	Water Resources Management and Engineering		Ongoing
Elsabeth Tsegaye	F	BDU	MSc	Engineering Hydrology	Mar-19	Completed
Dagnew Yehualie	M	BDU	MSc	Engineering Hydrology		Ongoing
Daniel Gelataw	M	BDU	MSc	Engineering Hydrology	Mar-19	Completed
Anna Larsson	F	SLU	MSc	Department of Soil and Environment SLU	Mar-19	Completed
Ayandis Worku	M	BDU	MSc	Water Resources Management and Engineering	Feb-18	Completed
Tadisual Asamin	M	BDU	MSc	Engineering Hydrology	Oct-18	Completed
Addisu Wondimnew Bezabih	M	BDU	Msc	Chemical Engineering	Oct-17	Completed
Negus Fentahun	F	BDU	MSc	Water Resources Management and Engineering	Oct-17	Completed

8. Utilization of Research Outputs

In USAID parlance, the results of cooperative agreements move from inputs to outputs to outcomes to impact. Outcomes state results in terms of utility or application in practice and impact includes downstream consideration of the scope and degree of adoption and use of results in the public and private sectors. Assessment of impact requires many years for the knowledge or technology to be put to practice. Recognizing the contemporary USAID strategy, and to the extent possible at the end of the experimental phase of this continuum, it is useful to estimate the overall result in terms of food security and resilience. Outcomes from the SIPSIN project can be addressed at the field, district, and national levels. At the field level, there have been instances of ongoing spontaneous adoption of SIPSIN results by adjacent and regional farmers who are adopting the systems that were studied. The collaboration with ILSSI has also provided some local infrastructure, such as microfinance and sale and maintenance of mechanical equipment, to support the further adoption and use of SIPSIN results. Training given to females in participating households on the importance of nutrition, especially to infants and young children will have a lasting and hopefully an expanding local impact. Regional bureaus and the Blue Nile (Abbay) basin development authority, as well as local communities, were engaged in capacity development related to the high level of pesticide residues in shallow groundwater and surface water bodies. The regional bureaus committed to adopting regulatory standards and monitoring in the future. In collaboration with ILSSI, the SIPSIN results have been scaled from local to national levels and related to national-level planning for future investments in irrigation related public and private sector investments. In Ethiopia, at their request, relevant ministries and the Agricultural Transformation Agency have been provided training and mentoring in the use of the IDSS as a tool, which they plan to use in making future investments in development. The relatively early interest and acceptance of the results of the SIPSIN-ILSSI collaboration by national decision-makers offer the prospect of the major impact of this research at the national level. The use by farmers of more informed and rigorous application of farming system approaches in SIPSIN, the appropriate use of water resources and the emergence of related infrastructure to support the use of irrigation all contribute to the improvement of food security at the farm and national levels. The sustainable use of irrigation, especially in the dry season and during periods of drought, is a critically important contribution to enhanced resilience in Ethiopia and elsewhere in the developing world.

9. Future Challenges and Opportunities

Sustainable intensification is recognized as a critical component in meeting the demands for increased food in the developing world. The prudent use of limited natural resources, especially soil and water, is necessary for success. Already degraded soils and polluted water supplies in many parts of sub-Saharan Africa impose major challenges to future success. SIPSIN emphasized the role of irrigation as a part of a sustainably intensified system for food production in Ethiopia and demonstrated that household nutrition is improved using these systems. The multiple farming systems evaluated in SIPSIN demonstrate the ability to produce more food with minimal environmental consequences. The optimal rate of application of irrigation is an example of making the best use of this limited resource. The scaling of SIPSIN results to the national level shows that there is excellent potential for larger irrigation schemes in Ethiopia that bring together appropriate soil and water resources, farmers and the related infrastructure and the potential for new and better marketing systems.

The ability to apply the results of SIPSIN (and potentially other SIIL products) at the national level, using the analytic methods advanced in these studies is a major step forward in taking farm-scale results to practice in national programs. Governments are challenged to eliminate constraints and create opportunities to enhance the sustainable development of food production. Going forward, there is an urgent need to encourage and enable the development of related infrastructure for sustainable intensification in both the private and public sectors. This is exemplified by the need for microfinance and the ability to purchase and maintain equipment such as solar panels for pumping water. Ongoing training and education at all levels in the developing world – including the use of decision support systems that provide the ability to plan and evaluate the best use of natural resources in intensified production systems is a key challenge that can be turned into an opportunity.

During the SIPSIN studies, Texas A&M proposed on multiple occasions that the analytic methods developed under the IDSS have substantial potential as an addendum to the analytic methods embodied in the SIIL SIAF. A comprehensive paper was prepared on this subject for SIIL management. This final report shows how the IDSS was used to assess the impact of SIPSIN on the five major domains of the SIAF. The SIAF provided a means of showing the interrelationships between complex variables studies and a means of visualizing the integrated product of this study. A web-based version of the analytic methods along with a simplified dashboard for use of the IDSS at local levels is envisioned for the future.

In December 2018, ILSSI was extended for an additional five years with the potential for increased funding. The emphasis of the extension will be on enhancing technology transfer and putting results of the initial phase to practice. The SIPSIN product contributes to the knowledge and technology needed to move the enhanced farming systems and related irrigation use forward.

10. Publications

The following list also contains ILSSI reports made to USAID noting the relationship with SIIL via SIPSIN although they do not specifically show joint attribution.

Publications In Peer-Reviewed Journals

1. Abeyou W., Yihun D., Petra S., Jaehak J., Manyowa M., Thomas G., Raghavan S., Nicole L., Neville C., (2019). Water resource assessment, gaps, and constraints of vegetable production in Robit and Dangishta watersheds, Upper Blue Nile Basin, Ethiopia. *Journal: Agricultural Water Management.* AGWAT_105767

2. Abeyou W., Jaehak J., Yihun D., Javier O., Petra S., Tom G., R. Srinivasan, and Neville C., (2017). Assessing potential land suitable for surface irrigation using groundwater in Ethiopia. Applied Geography 85 (2017) 1-13.
3. Assefa T., Jha M., Worqlul A.W., Reyes M., & Tilahun S., (2019). Scaling-Up Conservation Agriculture Production System with Drip Irrigation by Integrating MCE Technique and the APEX Model. *Water*, *11*(10), 2007.
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5. Assefa T., Jha M., Reyes M., Srinivasan R., & Worqlul A., (2018). Assessment of suitable areas for home gardens for irrigation potential, water availability, and water-lifting technologies. *Water*, *10*(4), 495.
6. Baye K., Choufani J., Mekonnen D., Bryan E., Ringler C., Griffiths J.K., & Davies E., (2019). *Irrigation and Women's Diet in Ethiopia A Longitudinal Study* (Vol. 1864). Intl Food Policy Res Inst.
7. Belay S.A., Schmitter P., Worqlul A.W., Steenhuis T.S., Reyes M.R., Tilahun S.A. (2019). Conservation Agriculture Saves Irrigation Water in the Dry Monsoon Phase in the Ethiopian Highlands. *Water 11:2103*.
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10. Moges M.A., Schmitter P., Tilahun S., Dagnaw D.C., Akale A.T., Langan S., Steenhuisen T. (2016) Suitability of Watershed Models to Predict Distributed Hydrologic Responses in the Awramba Watershed, Upper Blue Nile Basin (Online, Land Degradation & Development 28; 4: 1386–1397).
11. Moges M., Schmitter P., Tilahun S., Ayana E., Ketema A., Nigussie T. and Steenhuis T. (2017) Water Quality Assessment by Measuring and Using Landsat 7 ETM+ Images for the Current and Previous Trend Perspective: Lake Tana Ethiopia. Journal of Water Resource and Protection, 9, 1564-1585. DOI: 10.4236/jwarp.2017.912099.
12. Moges M.A., Schmitter P., Tilahun S.A. et al. 2018. Watershed modeling for reducing future non-point source sediment and phosphorus load in the Lake Tana Basin, Ethiopia. J Soils Sediments 18: 309. https://doi.org/10.1007/s11368-017-1824-z
13. Passarelli S., Mekonnen D., Bryan E., & Ringler C. (2018). Evaluating the pathways from small-scale irrigation to dietary diversity: evidence from Ethiopia and Tanzania. *Food Security*, *10*(4), 981-997.
14. Tewodros T. Assefa, Manoj K. Jha, Seifu A. Tilahun, Ephrem Yetbarek, Anwar A. Adem and Abeyou Wale. 2015. Identification of Erosion Hotspot Area using GIS and MCE Technique for Koga Watershed in the Upper Blue Nile Basin, Ethiopia. American Journal of Environmental Sciences. *Volume 11, Issue 4. Pages 245-255*
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17. Baye K., Choufani J., Mekonnen D., Bryan E., Ringler C., Griffiths J.K., & Davies E. (2019). *Irrigation and Women's Diet in Ethiopia a Longitudinal Study* (Vol. 1864). Intl Food Policy Res Inst.

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1. Tilahun S., T. Steenhuis, D. Lijalem, A. Yimer, A. Mamo, P. Schmitter. 2017. Observations and Parameter Efficient Distributed modeling of Surface runoff, and Groundwater recharge in Northern Ethiopia Highlands: the Case of Robit Bata and Dangishta Watersheds. ILSSI Technical report.
2. Bahir Dar University. 2018. Report on Nutrition training for women farmers in Dangishita Kebele, Dangila, Ethiopia

3. Gebregziabher G., H. Hagos, 2017. Economic feasibility of water lifting technologies for small scale irrigation in Ethiopia. ILSSI Technical report.
4. Prossie N., Petra S., Seifu T., Melaku T., Hanibal M., Tesfaye E., Desalegn T., Jennie B., Simon L., 2017. Testing appropriate smallholder irrigation technologies for increased and sustainable agricultural production in Ethiopia. ILSSI Technical report.

Conference Presentations

1. Sisay, A. *Response of onion irrigation water use and yield to conservation agriculture under different irrigation scheduling in the sub-humid region of the Blue Nile basin*. The Second Amhara Agricultural Forum. January 2018. Bahir Dar, Ethiopia.
2. Feleke, K. *Agro-chemical analysis from intensified production (SIPSIN*). ILSSI National Stakeholder Engagement Workshop, 24th May 2018, ILRI Campus, Addis Ababa.
3. Feleke, K. *Evaluation of shallow groundwater nutrient contamination in agricultural intensifying area of Lake Tana basin, Ethiopia*. 6th International Conference on the advancement of Science and Technology, 5 to 7 Oct 2018, Bahir Dar.
4. Feleke K. *Endosulfan pesticide dissipation and residue levels in khat and onion in a sub-humid region of Ethiopia*. 7th International Conference on the advancement of Science and Technology, 2 to 4 Aug 2019, Bahir Dar
5. Daniel G. Eshete. *Evaluation of Shallow Ground Water Recharge and its Potential for Dry Season Irrigation at Brante Watershed, Dangila, Ethiopia*. 7th International Conference on the advancement of Science and Technology, 2 to 4 Aug 2019, Bahir Dar
6. Minychl G. Dersseh. *Dynamics of eutrophication and its linkage to Water hyacinth on Lake Tana, Upper Blue Nile, Ethiopia: Understanding Land-Lake interaction and process*. 7th International Conference on the advancement of Science and Technology, 2 to 4 Aug 2019, Bahir Dar.
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9. Mwilawa A.J., Ngunga D., and Lukuyu B., *On-farm participatory forage evaluations of Pennisetum purpureum cultivars in sub-humid low and mid-altitude areas, Tanzania* presented in 40th TSAP Conference
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12. Reyes M. *Comparing Vegetable Yield of Conventional versus Conservation Agriculture Production Systems in Eight Countries*. First International Sustainable Agricultural Intensification and Nutrition. Royal University of Agriculture, Phnom Penh, Cambodia. Jan 10-11, 2018.
13. Fentahun N., Tilahun S.A., Yimer A., Assefa T.T., Jha M.K., Reyes M.R. *Evaluating water productivity and crop coefficients of Cabbage crops under conservation agriculture with drip irrigation system in Robit kebe*. The *2nd Amhara Agricultural Forum*, Bahir Dar, Ethiopia, Jan 16, 2018.
14. Adie, M. Bezabih, A. Yitayew, B.Demeke, L. Yeheyis, M. Blümmel. *Lessons from pilot trials with small-scale irrigated forage production in the Amhara Region: the potential of integrating the perennial forage Napier grass with Desmodium and Pigeon Pea in cropping systems*. The Second Amhara Agricultural Forum 2017, Hosted by Bahir Dar University and the Small Scale and Micro Irrigation for Ethiopian Smallholders Project

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15. Nigues F., Seifu A. Tilahun, Abdu Yimer, Tewodros T. Assefa, Manoj K. Jha, Manuel R. Reyes. *Evaluating Water Productivity and Crop Coefficients of Cabbage Crops under Conservation Agriculture with Drip Irrigation System in Robit Kebele*. The Second Amhara Agricultural Forum 2017, Hosted by Bahir Dar University and the Small Scale and Micro Irrigation for Ethiopian Smallholders Project in Collaboration with IWMI. Small Scale Irrigation and Agricultural Technologies for Sustainable Development in Amhara Region. Bahir Dar, Ethiopia, January 2018.
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17. Habtamu Muche, Misba Abdela, Petra Schmitter, Prossie Nakawuka, Seifu Admasu Tilahun, Tammo Steenhuis, Jennie Barron, Abera Adie, Michael Blummel. *Biological and mechanical techniques to increase infiltration in rainfed agriculture of the Ethiopian highlands*. The Second Amhara Agricultural Forum 2017, Hosted by Bahir Dar University and the Small Scale and Micro Irrigation for Ethiopian Smallholders Project in Collaboration with IWMI. Small Scale Irrigation and Agricultural Technologies for Sustainable Development in Amhara Region. Bahir Dar, Ethiopia, January 2018.
18. Abeyou W. Worqlul, Thomas Gerik, Yihun T. Dile, Jean-Claude Bizimana, Jaehak Jeong, Petra Schmitter, R. Srinivasan, James W. Richardson and, Neville Clarke. 2018. *Small Scale Irrigation within Water, Energy and Food Nexus Framework in Ethiopia*. The Second Amhara Agricultural Forum 2017, Hosted by Bahir Dar University and the Small Scale and Micro Irrigation for Ethiopian Smallholders Project in Collaboration with IWMI. Small Scale Irrigation and Agricultural Technologies for Sustainable Development in Amhara Region. Bahir Dar, Ethiopia, January 2018.
19. Dawit Mekonnen. *Irrigation-Nutrition Linkages*. Ethiopian Public Health Institute, 7 December 2018, Addis Ababa.
20. Dawit Mekonnen. *Irrigation-Nutrition Linkages*. USAID Mission Ethiopia, 11 February 2019, Addis Ababa.
21. Claudia Ringler. *Irrigation-Nutrition Linkages: What's New?* Stockholm World Water Week, 27 August 2019.
22. Dawit Mekonnen, Claudia Ringler, Elizabeth Brian, and Jowel Choufani. *ILSSI Project Research Results and Outcomes*. ILSSI National Stakeholder Engagement Workshop, 24th May 2018, ILRI Campus, Addis Ababa.
23. Claudia Ringler, Dawit Mekonnen, Elizabeth Bryan, and Jowel Choufani. *Preliminary finding on irrigation-nutrition-gender linkages*. USAID brown bag seminar, 12th July 2018, Ronald Raegan Building, Washington DC.
24. Seifu Tilahun. *SSI and risks of intensification: A case study on water quality in the Ethiopian Highlands*. Stockholm World Water Week 2018.
25. Dawit Mekonnen, Simone Passarelli, Elizabeth Bryan, and Claudia Ringler. *Irrigation-nutrition linkages: Insights from the ILSSI project and beyond*. Stockholm World Water Week 2016.
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27. Claudia Ringler. *How irrigation supports nutrition outcomes. New Insights*. October 1, 2019. ZEF, Bonn, Germany.

Posters

1. Assefa T.T., M.K. Jha Conservation agriculture and drip irrigation in commercial vegetable home gardens: an experiment and modeling. College of Engineering graduate poster presentation competition, North Carolina A&T State University. April 2017.
2. Assefa T.T., M.K. Jha, M.R. Reyes, R. Srinivasan, A.W. Worqlul. 2016. Evaluation of land suitability for irrigation and potential of water sources using GIS and MCE technique for Lake Tana Basin. Annual International Conference of the American Society of Agricultural and Biological Engineers (ASABE). July 17-20, 2016, Orlando, Florida.

3. Worku A., N. Fentahun, S.A. Tilahun, Yimer A., T.T. Assefa, M.K. Jha, M.R. Reyes. Conservation agriculture with drip irrigation. *Feed the Future Ethiopia under Value Chain Activity program*, Finote Selam Town, West Gojjam, Ethiopia, Jan 26-28, 2018.
4. Tesfaye M.Z., Daba T., Bizimana J.C., Balana B. and G. Gebregziabher. Farmers Willingness to Pay for Smallholder Water Lifting Technologies: Evidence from Ethiopia. Poster presentation at the Agricultural and Applied Economics Association (AAEA) annual meeting, July 21-23, 2019, Atlanta – Georgia.
5. Yihun T. Dile, Worqlul A.W., Xie H., Ayana E.K., Bizimana J.C., Srinivasan R., You L., Lefore N., Gerik T., Richardson J.W., & Clarke Neville. (2018). Potential of Small Scale Irrigation to Improve Livelihoods in Ethiopia. In AGU - American Geophysical Union.
6. Abeyou W. Worqlul, Sisay Asres, Yihun T. Dile, Jean-Claude Bizimana, Tewodros Assefa, Seifu A. Tilahun, Thomas Gerik, Nicole Lefore, R. Srinivasan, James W. Richardson and Neville Clarke (2018). Sustainable Intensification Assessment of Conventional and Conservation Agriculture in Ethiopia. In Bahir Dar University, Ethiopia.

Presentations For Stakeholder Engagement

1. Seifu A Tilahun, Addisu Wondimneh, Feleke K. Sishu, Petra Schmitter, Amare Haileslassie, Tammo Steenhuis. 2 August 2017. Assessment of Pesticides pollution levels due to agricultural intensification. Presentation to the Environmental, Forest and Wildlife Protection and Development Authority and the Abay Basin Authority as part of stakeholder engagement to monitor, regulate and build capacity related to mitigating pollution levels related to irrigated agriculture.

Ancillary Reports

These ILSSI reports made to USAID note the relationship with SIIL via SIPSIN although they do not specifically mention joint attribution.

1. Feed the Future Innovation Lab for Small Scale Irrigation Semi-Annual Report October 1, 2016 -March 31st, 2017

2. Feed the Future Innovation Lab for Small Scale Irrigation Mid-Term Report, 2014 - 2016

3. Feed the Future Innovation Lab for Small Scale Irrigation Annual Report October 1, 2015 – September 30, 2016

4. Feed the Future Innovation Lab for Small Scale Irrigation Semi-Annual Report October 1st, 2015 – March 31st, 2016

5. Feed the Future Innovation Lab for Small Scale Irrigation Semi-Annual Report April 1st – September 30, 2015

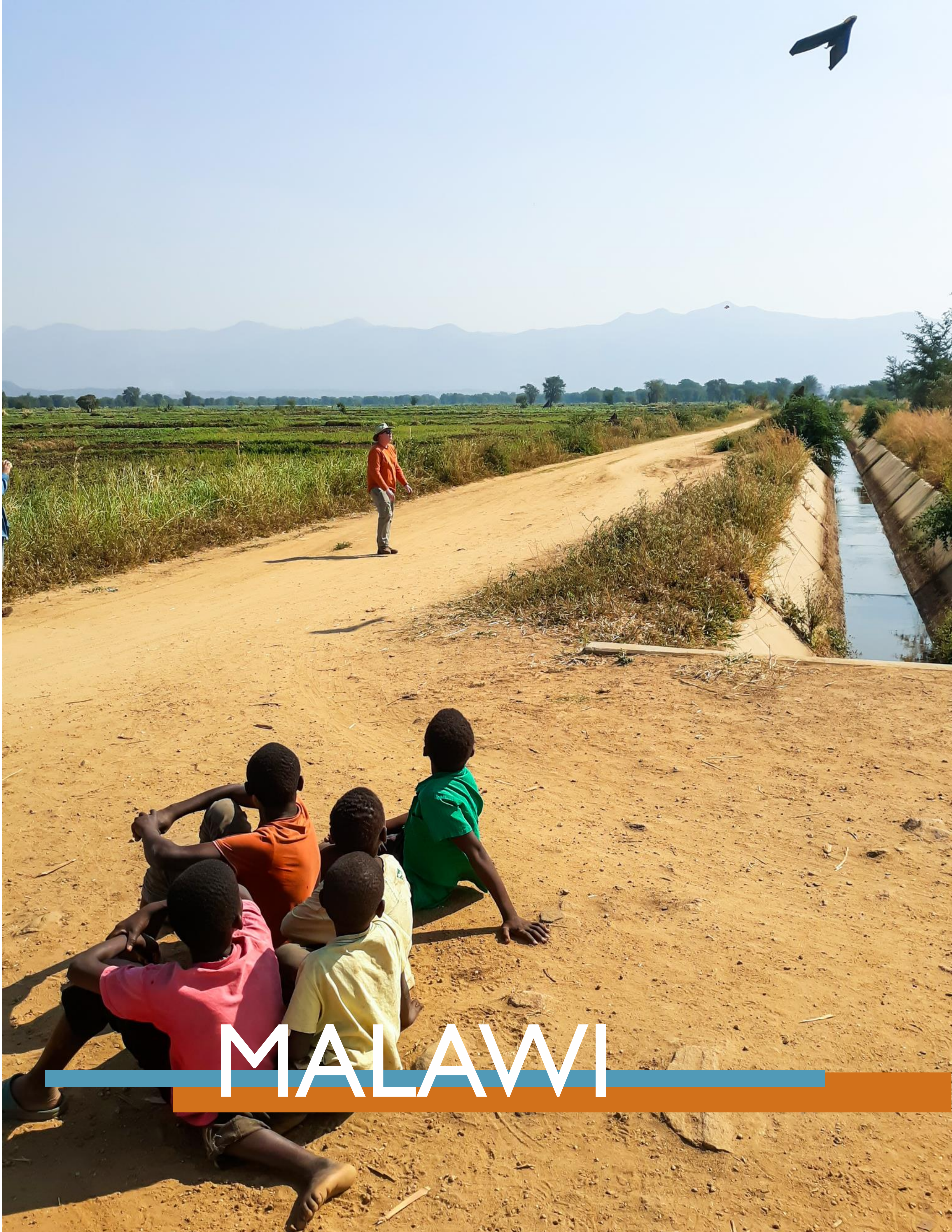
6. Feed the Future Innovation Lab for Small Scale Irrigation Semi-Annual Report October 1st, 2015 – March 31st, 2016

7. Bryan, Elizabeth; Chase, Claire; and Schulte, Mik. 2019. Nutrition-sensitive irrigation and water management. Washington, DC: World Bank. http://hdl.handle.net/10986/32309

11. Datasets Produced

Dataset	Repository	Notes
Water quality data (N, P, and pesticides) in groundwater and surface water in Robit	SIIL Dataverse	International Water Management Institute
Water quality data (N, P, and pesticides) in groundwater and surface water in Dangista	SIIL Dataverse	International Water Management Institute
Sustainably Intensified Production Systems Impact on Nutrition (SIPSIN) Round 1, Ethiopia	SIIL Dataverse	International Food Policy Research Institute
Sustainably Intensified Production Systems Impact on Nutrition (SIPSIN) Round 2, Ethiopia	SIIL Dataverse	International Food Policy Research Institute
Sustainably Intensified Production Systems Impact on Nutrition (SIPSIN) Round 3, Ethiopia	SIIL Dataverse	International Food Policy Research Institute
ILSSI/IFPRI study on irrigation, gender, and nutrition	SIIL Dataverse	International Food Policy Research Institute
Yield and fodder quality of irrigated Napier grass inter-cropped with either Sesbania, Desmodium or Pigeon pea	ILSSI Dataverse	International Livestock Research Institute
Price and quality of feed resources collected from Bahir Dar zuria and other districts of Amhara region	ILSSI Dataverse	International Livestock Research Institute
Effect of intercropping forages with maize in conventional tillage and conservation agriculture	SIIL Dataverse	International Livestock Research Institute
Upscaling Soil and Water Assessment Tool Data for Ethiopia	ILSSI Dataverse	Integrated Decision Support System - IDSS
Ex-post, Gap and Constraint Farm Simulation Model Data	ILSSI Dataverse	Integrated Decision Support System - FARMSIM
Conservation agriculture (CA) practice	ILSSI Dataverse	Integrated Decision Support System - Apex
Ex-post Agricultural Policy/Environmental eXtender Data: Conventional tillage (CT)	ILSSI Dataverse	Integrated Decision Support System - APEX
Ex-ante Agricultural Policy/Environmental eXtender Data for the Dangesheta Watershed	ILSSI Dataverse	Integrated Decision Support System - APEX
Ex-post Agricultural Policy/Environmental eXtender Data: Multiple cropping systems	ILSSI Dataverse	Integrated Decision Support System - APEX
Ex-ante Agricultural Policy/Environmental eXtender Data -Mikindo	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data - Yemu	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data -Robit	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Ghana Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data -Mikindo	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Ghana Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Robit Watershed	ILSSI Dataverse	North Carolina A&T

Dataset	Repository	Notes
Ex-ante Agricultural Policy/Environmental eXtender Data for Mkindo Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Robit Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Dangishita Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Robit Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Ethiopia Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Dangishita Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for the Mkindo Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data - Dangesheta	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Dangesheta Watershed	ILSSI Dataverse	North Carolina A&T
Ex-ante Agricultural Policy/Environmental eXtender Data for Dangishita	ILSSI Dataverse	North Carolina A&T



MALAWI

East Africa
Malawi

Precision Agriculture for Smallholder Systems in Africa

1. **Lead Institution:** Michigan State University (MSU)
    - U.S. Collaborating Institutions:
        - Oakland University

2. **Research Team:**
    - Lead Investigator:
        - Joe Messina, MSU
    - Co-Investigators:
        - Brad Peter, Michigan State University/University of Alabama
        - Sieglinde Snapp, Michigan State University
        - Jon Carroll, Oakland University
        - William Burke, Agricultural & Food Policy Consulting
        - April Frake, Michigan State University/University of Alabama
        - Shengpan Lin, Michigan State University

3. Executive Summary

Precision agriculture has become a prominent point of focus in remote sensing science since the mass production of affordable individual-use unmanned aerial systems (sUAS). While commercial and national government satellites have been monitoring agriculture since the 1970s, recent advancements in sUAS have facilitated unprecedented levels of geospatial data for farming systems optimization. Variable-rate technology, the practice of allocating farm improvements based on spatial measurements of crop status, is now common in industrial agriculture, but these technologies have not yet been effectively leveraged for the smallholder farming context in the less-developed world.

Of particular interest here is the potential to conduct precision agriculture at multiple scales of analysis for small-holder systems. First, what are the actionable spatial resolutions (from sUAS to satellite systems) and appropriate spectral indices for conducting intra-farm precision agriculture in smallholder systems? Second, what recommendations can be made from multi-scale geospatial measurements of crop status? Third, what farm applications, decision-making opportunities, and yield predictions offer the greatest return on investment?

Given substantial previous USAID Feed the Future investments, we selected Malawi and our existing trial farming communities in Nyambi and Ntubwi. In February 2018, we collected image data of the experimentation farms using a senseFly eBee agriculture drone equipped with a high spatial resolution multispectral camera. Flights were conducted at multiple heights to produce images of varying spatial resolutions from the maize plant scale (27-cm) down to the leaf scale (7-cm). Image collection took place during peak maize production (February 20, 2018). To evaluate a complete range of spatial resolutions, all cloud-free commercial (Planet, SPOT, and Pléiades) and government satellite (Sentinel-2) data available during the time of the sUAS missions were acquired. Multispectral imagery acquired was related to on-farm measurements of crop chlorophyll content and yield using a collection of models.

In Malawi, where the landscape is highly heterogeneous at local scales, sUAS are critical for evaluating intra-farm variability. Outcomes of this research suggest that the only viable scale of analysis for conducting precision agriculture in the smallholder context is currently via sUAS. At coarser spatial resolutions, such

as those offered by Pléiades, Planet, SPOT, and Sentinel-2 (2-m, 3-m, 6-m, and 20-m, respectively), there is a substantial drop-off in the ability to accurately measure intra-farm variability. However, if satellite sensor spatial resolutions are further refined, revisit rates are improved, and data gathering can penetrate the cloud layer (such as radar-based systems), then satellites may theoretically perform as effectively as sUAS in the smallholder context. Interestingly, we found that the finest spatial resolution images (7-cm) were not the most effective, attributed in part to soil/shadow mixing with vegetation signals. The results of this study showed that imaging at spatial resolutions nearer the maize plant scale (14- and 27-cm) was the most effective. Consistent with other studies in this field, the analyses here also showed that spectral indices that utilize the green wavelength were most closely associated with crop chlorophyll content.

> The outcomes of this research are critical for the effective implementation of variable-rate technology. To make farm recommendations that are based on multispectral remote sensing, it is necessary to first establish the spatial resolutions and spectral indices that will produce the most accurate representation of crop status on the ground.

Following these findings, we have developed a framework for automating the process of index calculation and statistical metrics relating imagery to field observations. Additionally, a geospatial product that ingests remote sensing imagery and provides intra-farm recommendations, such as proportional fertilizer application, has been developed and is currently undergoing fine-tuning.

Finally, for farm guidance to be most effective, yield outcomes and return on investment from variable-rate technology require accurate predictions. Currently, most crop modeling systems are not natively designed to accommodate multispectral geospatial data. Future research in this area will benefit from agile crop modeling systems such as APSIM that have built-in functionalities for computing geospatial data and also utilize remote sensing-based measurements in the prediction algorithms. Objectives planned for future research in this area will include collaborations with crop system modelers, economists, and computer scientists to create open access precision agriculture tools that evaluate farm productivity, recommend variable-rate technologies, and predict the return on investment.

4. Project Partners

- Michigan State University:
  - Department of Geography, Environment, and Spatial Sciences
  - Department of Plant, Soil, and Microbial Sciences
  - Social Science Data Analytics Initiative
- The University of Alabama:
  - College of Arts & Sciences
  - Department of Geography
- Oakland University, Department of Sociology, Anthropology, Social Work and Criminal Justice
- Agricultural & Food Policy Consulting
- Africa RISING
- Lilongwe University of Agriculture and Natural Resources (LUANAR)
- International Center for Tropical Agriculture (CIAT)
- VIAMO

Potential Future Collaborations

- University of Malawi, Chancellor College
- Malawi University of Science and Technology (MUST)

- Established a relationship with Dr. David Mkwambisi, Head of the Centre for Innovation and Industrial Research. MUST is a partner of the African Drone and Data Academy that is being led by a research group from Virginia Tech with funding from UNICEF.

Group photo at LUANAR following a seminar and sUAS data applications demonstration. Photo by Emmanuel Jambo, assistant researcher at Africa RISING.

5. Project Goals and Objectives

Overall Goal

The purpose of this project was to collect and integrate multi-scale geospatial data and analytic techniques to generate inter- and intra-seasonal decision support guidance capable of improving Malawian smallholder farmers' agricultural productivity. Recent advances in data management and modeling and the commercialization of remote sensing tools have led to dramatic improvements in our understanding of the multi-scale spatial patterns of soils, weather and climate, and agricultural productivity. In short, the project sought to demonstrate the potential for remote sensing-based precision agriculture to transform smallholder farm production. This project gathered, analyzed, and translated multiscale geospatial data into actionable and localized farm level recommendations. The effort was guided by three overarching objectives:

Overall Objectives

The overall objectives guided the effort of the project to gather, analyze and translate multiscale geospatial data into actionable and localized farm level recommendations.

Objective 1: Develop and test a model for precision farming in the smallholder agriculture context.

- Use domain and context-specific data, multidimensional models, and theoretical frameworks from agronomy, economics, and geography design to deploy inter- and intra-seasonal tools for farm level, site-specific decision making.

- Evaluate the spatial and temporal variability of farm productivity (inter-farm and intra-farm) and potential yield gains from the use of high-resolution remotely-sensed imagery and implemented farming practices.

Objective 2: Combine new analytical tools and data into an integrated framework that provides actionable information for site-specific decision making.

- Construct a database of all available geographic/remote sensing-based biophysical data associated with agricultural production (precipitation, temperature, soil content, terrain properties, and solar radiation).
- Acquire multispectral satellite imagery across multiple spatial scales from commercial and national government platforms.
- Collect very high spatial resolution multispectral imagery via sUAS at the intra-farm scale.

Objective 3: Integrate and use proven and new analytic and dissemination tools for scalable decision support.

- Innovative avenues for making these new insights actionable for policymakers, agricultural extension systems, and local agricultural advisors from private and public sectors working with smallholder farmers.

6. Overview of Activities

Field data collections

The research conducted required a considerable and concerted field data collection effort. Experimentation farms evaluated in this study were maintained and designed by agronomy researchers affiliated with Michigan State University, Africa RISING, and the Lilongwe University of Agriculture and Natural Resources (LUANAR). Farm plots were set up to test maize response to variable fertilizer and nutrient treatments. Yield estimates were calculated for each plot and chlorophyll content measurements were collected using a handheld SPAD 502, which produces a reflectance index that has a demonstrated relationship with plant nitrogen and yield.

In February 2018, we visited Malawi to conduct multiple sUAS missions that were designed to retrieve high spatial resolution (7–27-cm) multispectral imagery (RGB, red, green, NIR, and red edge) at two Africa RISING experimentation farms in Machinga, Malawi. We deployed a senseFly eBee fixed-wing aircraft equipped with a Parrot Sequoia multispectral camera. SPAD measurements were collected for 54 plots among the two farms at Ntubwi and Nyambi.

In August 2019, another sUAS mission was conducted at Bwanje Valley Irrigation Scheme in Mtakataka, Malawi. Flight missions covered approximately one-third of the scheme. SPAD measurements were collected for 65 individual early growth stage maize plants in a mono-cropped field. This field collection effort took place at the plant scale during the dry season on irrigation whereas previous collections addressed the plot scale during the rainy season with a mature crop. Soil moisture measurements were collected at 56 sites across the imaging area. Imagery and field data will be used in part to identify areas of potential mosquito breeding habitats.

A portion of the maize field sampled using SPAD handheld chlorophyll meter. Photo by Brad Peter.

Seminar demonstration and training

Dr. Brad Peter, Dr. April Frake, and Dr. Jon Carroll organized a demonstrative and instructional seminar titled, "Monitoring Agricultural Productivity and Mosquito Breeding Potential via Remote Sensing and sUAS." Dr. Jon Carroll discussed the technical capabilities and logistics of planning sUAS collections for monitoring agriculture. Dr. Brad Peter discussed challenges associated with monitoring farm-scale agriculture and presented findings from researching multi-scale characterizations of agricultural productivity. Dr. Peter also highlighted the capabilities of Google Earth Engine as a geocommunication tool for sharing geographic data and modeled geographic products. Dr. April Frake discussed complex problems associated with improved food security by transforming land to irrigated agriculture while simultaneously increasing malaria vulnerability by creating a habitat for mosquito larvae. In-depth discussions were held following the seminar and fruitful new collaborative relationships are expected to emerge.

7. Accomplishments

- Constructed a database of all available geographic/remote sensing-based biophysical data associated with agricultural production at two experimentation farms. Acquired multispectral imagery across multiple spatial scales from commercial satellites, national government satellites, and sUAS.
- Developed and tested models for precision farming in the smallholder agriculture context. Geospatial products were developed that integrate agronomic data to facilitate inter- and intra-seasonal decision making at the farm scale.
- Leveraged new and innovative analytic and dissemination tools for scaling decision support. Geocommunication and actionable data supplied to policy-makers and agricultural extension advisors via interactive Google Earth Engine applications.

8. Utilization of Research Outputs

The research conducted in this project has a direct impact on the way precision agriculture is conducted in the smallholder farming context. Importantly, this project offered evidence in an area of inquiry that is currently lacking information. Despite the utility of high-spatial resolution commercial and national government satellites, their limitations are not well understood; the findings of this project elucidate problems associated with clouds, spatial resolutions, and data errors in heterogeneous smallholder farming areas. Similarly, the evolving nature and rapid advancement of sUAS is continually producing new challenges and questions. One topic that has not been sufficiently addressed is what spatial resolutions are optimal for relating multispectral images to on-farm productivity. sUAS imagery implemented in crop system models will benefit from data collection modes that consider optimal spatial resolutions and spectral indices during flight mission planning. The methods used here are transferable and can be used to evaluate any crop; the workflow is published on Harvard Dataverse and the related manuscript has been accepted for publication.

Geocommunication Products

To enhance the utility of the research conducted, several open access geospatial data applications were developed and published. In communicating academic geographic information science, there were previously technological barriers that hindered digital map product sharing.

New technologies such as ArcGIS Online and Google Earth Engine have enabled more geospatial data viewing and interaction. The ability to pan, zoom, and query a map is an invaluable advancement that cannot take place on a standard page printing.

All of the geocommunication products listed below are freely available and require only a connection to the internet.

- The outlier detection and visualization application developed using Google Earth Engine is an open-access platform that allows users to identify and map spatial outliers and data distribution outliers. In the context of agriculture, this tool can aid in locating farms with marginal to very low production, farms that are highly productive or identify anomalous data that is the result of measurement error. http://outliers.cartoscience.com

- The time-series remote sensing data comparison application allows users to compare any two spatial data products stored on the Google Earth Engine repository. As satellite sensors advance and model algorithms change, different versions of the same product emerge, occasionally with profound differences. When using remote sensing data to monitor agricultural productivity, it is critical to select data products that match the reality on the ground and are as close to error-free as possible. http://versions.cartoscience.com

- What crops can grow where? And when? This crop niche mapping application allows users to visualize the fundamental climate niche of any crop, anywhere on the globe, during any temporal range and seasonal window. http://cropniche.cartoscience.com

- The modifiable areal unit problem (MAUP) is one of the fundamental concepts in geographic information science that exposes challenges associated with data classifications or aggregations changing depending on the areal unit under study. This is a geocommunication application that demonstrates these issues: http://maup.cartoscience.com

- When and where are the tropical clouds? Clouds are one of the dominant hurdles when imaging agriculture during Malawi's unimodal growing season. This geocommunication product depicts 18 years' worth of cloud cover throughout the tropics aggregated by frequency each month. http://clouds.cartoscience.com

- Where is global agriculture? There are many land-use/land-cover maps at our disposal, but in some geographies the agreement among them is low. This geocommunication product highlights problems associated with different land-cover classification systems leading to different results. http://agriculture.cartoscience.com

9. Future Challenges and Opportunities

Return On Investment: Crop Modeling And Variable-Rate Technology

With increasingly fine spatial resolution data, precision agriculture is poised to enter advanced intra-farm scales of analysis. Remote sensing offers data that is synergistic with many crop system models; however, there are substantial barriers in retrieving climate and crop information at local scales due to problems of clouds, sensor ground sampling distance, and satellite revisit rates. At present, the spatial variability of intra-farm predictions is largely driven by soil quality measurements and management practices, and precipitation/temperature variability may be exclusively temporal. In this regard, yield and return on investment prediction accuracy will benefit from local climate data and crop system models that integrate remote sensing metrics in their algorithms.

Downscaling global climate data to the farm-scale can offer finer spatial resolution climate information; however, there is some contention regarding the accuracy of climate downscaling, particularly in sensor poor areas of the world, and large errors emerging due to crop model sensitivity.

Dual Impact Solutions: Cropping Systems For Soil Rehabilitation And Nutrient Diversity

Field work in Malawi. *Photo credit: Joseph Messina.*

Three of the United Nations Sustainable Development Goals are to increase agricultural production, eliminate hunger, and end malnutrition. Pigeonpea integration into maize-based cropping systems is a practice that many agronomists promote for rehabilitating soils on smallholder farms in Malawi. Also, one byproduct of introducing crop biodiversity is that it also supports household nutrient diversity. Considering pigeon pea suitability, maize suitability, and various types of crop arrangements, the scaling potential of biodiverse systems can be mapped through the lens of nutrition. In this case, the land equivalent ratio (LER) can be used to evaluate the tradeoffs between yield, calories, and nutritional properties for various spatial arrangements of pigeon pea and maize on a farm. Comparing maps such as these with food insecurity indicators and measures of agricultural productivity may prove valuable for scaling improved food security, nutrition, sustainable agriculture, and environmental conservation.

Parsing Crop Types In Heterogeneous Landscapes With Suas Imagery

There are two studies planned immediately following this research that will further utilize imagery collected via sUAS in Malawi. First, land-use classification analyses of the smallholder agriculture environment. National government satellites (e.g., MODIS) are insufficient for categorization where land-use is highly mixed and subtle thresholds determine classification. At 7–27-cm spatial resolution, distinguishing unique combinations of spectral signals from different crops may be possible. Multispectral image data alongside visual image interpretation and field data collections on crop type will be used for supervised classifications such as support vector machine (SVM) and classification and regression trees (CART) approaches. This assessment will also evaluate the effectiveness of each spatial resolution (7-cm, 14-cm, and 27-cm). Second, a data mining effort similar to the research here will be conducted but will include a more exhaustive collection of precision agriculture spectral indices to generate a massive data set of multiple regression permutations.

Near Real-Time Crop Niche Mapping On The Cloud

Remote sensing-based characterizations of crop suitability are common; however, these products generally address singular time intervals, variable collections of crops, and are sometimes presented with ambiguous suitability classifications. Many static maps are subject to diminishing relevance over time, particularly as global changes continue to occur. The most notable crop suitability maps are the Global Agro-Ecological Zones (GAEZ) product distributed by the Food and Agriculture Organization of the United Nations. Despite the value that these products offer, they are not always current and may rely on future predictions rather than empirical data. Recently, cloud-based alternatives such as Google Earth Engine offer efficient large-scale geospatial computing. Shifting the crop niche mapping paradigm, web-based GIS enables the transformation of static maps to a dynamic form that is interactive and temporally continuous. The argument posed here is that crop suitability maps can and should be produced at the same rate climate and land data are procured, giving more timely decision power to agronomists, government stakeholders, and policymakers to effectively scale agricultural improvement and respond to crises.

10. Publications

Academic Publications

1. Peter B.G., Messina J.P., Lin Z., and Snapp S.S. [*in preparation*]. What crops can grow where? A continuously updatable crop climate-suitability geovisualization application for Google Earth Engine.
2. Frake A.N., Peter, B. G., Messina, J.P., and Walker E. [*in preparation*]. Leveraging big data for public health: Irrigation and malaria vulnerability in Malawi.
3. Frake A.N., Namaona W., Walker E., and Messina J. P. [*in review*]. Estimating Spatio-temporal distributions of mosquito breeding pools in irrigated agricultural schemes: A case study at the Bwanje Valley Irrigation Scheme.
4. Peter B.G., Messina J.P., Carrol J., Lin S., Chimonyo V., Zhi J., and Snapp S.S. [*accepted* 10/2019]. Multi-resolution satellite and UAS imagery for precision agriculture on smallholder farms in Malawi. *Photogrammetric Engineering & Remote Sensing*.
5. Snapp S.S., Cox C., and Peter B.G. 2019. Multipurpose pulse crops for smallholders in Sub-Saharan Africa: Identification of promising 'scale-out' options. *Global Food Security* 23:22– 32.
6. Peter B.G., and Messina J.P. 2019. Errors in time-series remote sensing and an open-access application for detecting and visualizing spatial data outliers using Google Earth Engine. *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing* 12(4):1165–1174. DOI: 10.1109/JSTARS.2019.2901404.
7. Snapp S., Rogé P., Okori P., Chikowo R., Peter B.G., and Messina J.P. 2019. Perennial grains for Africa: possibility or pipedream? *Experimental Agriculture* 1–22. DOI: 10.1017/S0014479718000066.
8. Peter B.G., Messina J.P., and Snapp S. 2018. A multi-scalar approach to mapping marginal agricultural land: Smallholder agriculture in Malawi. *Annals of the American Association of Geographers* 108(4):989–1005. DOI: 10.1080/24694452.2017.1403877.
9. Frake A.N. and Messina J. P. 2018. Scaling up: More precision, less novelty. *Sustainability* 10(3):835. DOI: 10.3390/su10030835.
10. Peter B.G., Mungai L., Messina J., and Snapp S. 2017. Nature-based agricultural solutions: Scaling perennial grains across Africa. Environmental Research 159:283–290. DOI: 10.1016/j.envres.2017.08.011
11. Peter B.G., Messina J., Frake A., and Snapp S. Scaling agricultural innovations: Pigeonpea in Malawi. 2017. The Professional Geographer 70(2):239–250. DOI:10.1080/00330124.2017.1347798

Conference Presentations

1. Messina J.P., Peter B.G., Carroll J.W., Mungai L.M., and Snapp S.S. 2019. Precision Agriculture for Smallholder Systems in Africa. Department of Geography, The University of Alabama, College of Arts & Sciences. Colloquium presentation.
2. Peter B.G., Messina J.P., Carroll J.W., Lin S., Chikowo R., Chimonyo R., Jambo E., and Snapp S.S. 2019. Effective spatial resolutions for monitoring crop health on smallholder farms. Monitoring Agricultural Productivity and Mosquito Breeding Potential Via Remote Sensing and sUAS. Lilongwe University of Agriculture and Natural Resources.
3. Peter B.G., Messina J.P., Snapp S.S., and Carroll J.W. 2019. Remote sensing for precision agriculture: A multi-scale view of farm productivity. From the ground up: Improving soil health in Africa through partnership. Michigan State University.

4. Carroll J.W. 2019. Engaging the world: Oakland University archaeology on four continents. Rochester Hills Public Library. Rochester, MI.

5. Messina J.P., Peter B.G., Frake A.F., and Lin Z. 2018. Web-based GIS for geovisualizing environmental niche: Cropping systems and disease-transmitting vectors. Environmental Science & Policy Program—Balancing Act: Food, Water, Energy, Climate. Michigan State University.
6. Lin S., Peter B.G., and Messina J.P. 2018. Remote sensing accuracy and resolution for precision agriculture in small farms, Malawi. Spatial Accuracy Conference. Beijing, China.
7. Messina J.P., Peter B.G., Mungai L.M., and Frake A F. 2018. Scaling agricultural innovations in Malawi. American Association of Geographers Annual Meeting. New Orleans, LA.
8. Mungai L. and Messina J.P. 2018. Developing sustainable intensification (SI) of agriculture indicators for smallholder farming systems: A case study in Malawi. American Association of Geographers Annual Meeting. New Orleans, LA.
9. Frake A.N., Peter B.G., Messina J.P., and Walker E. D. 2018. Leveraging big data for public health: Mapping malaria vector suitability in Malawi using Google Earth Engine. American Society of Tropical Medicine & Hygiene. New Orleans, LA.

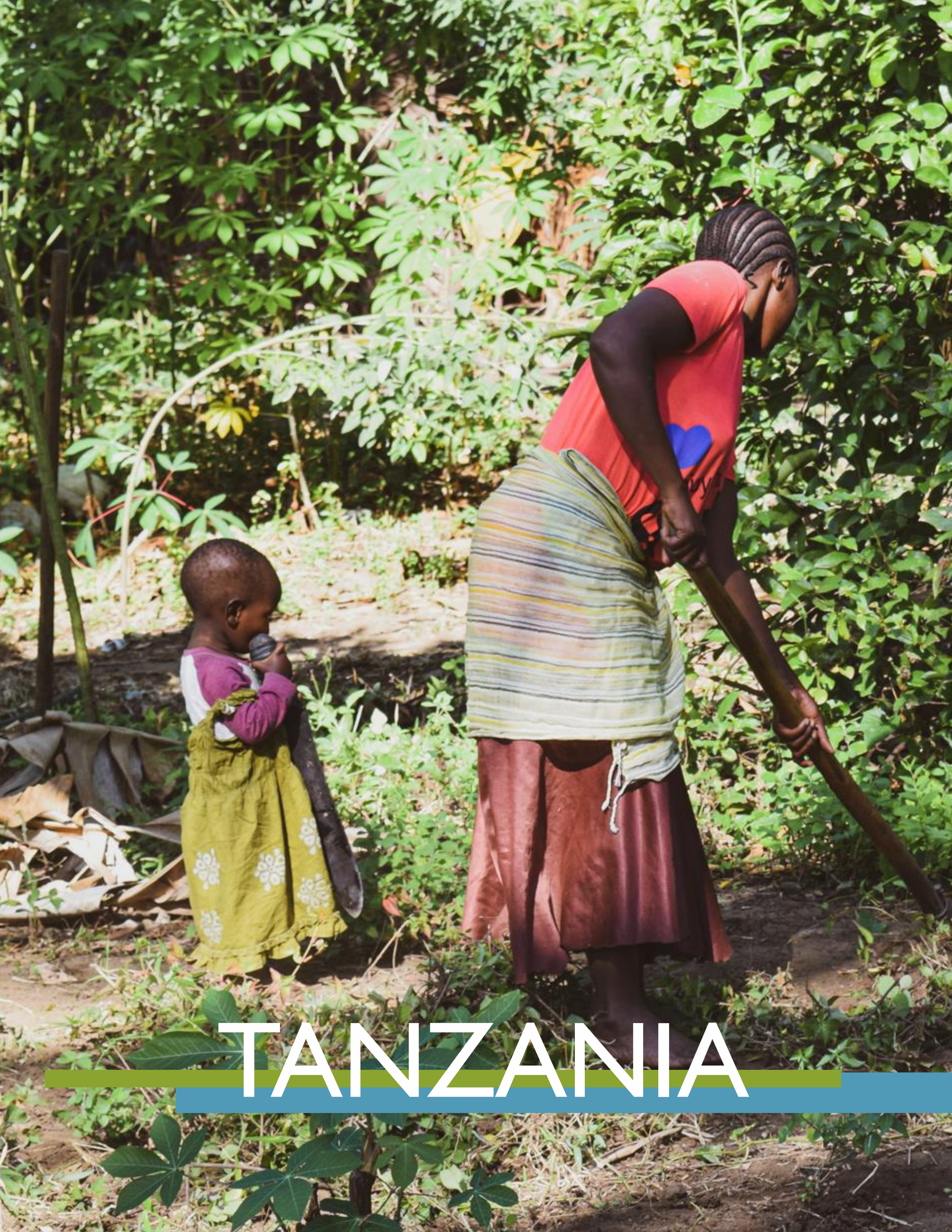
Outreach Publications And Events

1. Oakland University News. 2019. Anthropology professor deploys drone to fight disease in Africa. https://www.oakland.edu/oumagazine/news/socan/2019/anthropology-professor-deploys-drone-to-fight-disease-in-Africa. Oakland University.
2. Mid-Michigan College Guide. 2019. LCC and MSU partner up in the hot field of geospatial science. Wiswell, J.
3. The Detroit News. 2019. Michigan drones help crops, fight malaria in Africa. Krupa, G. https://www.detroitnews.com/story/news/local/michigan/2019/10/11/professors-oakland-university-and-Michigan-state-help-africa/2420650001/
4. Research@MSU. 2018. Remote-sensed data, crop modeling helps African farmers. Forster, M. http://engagedscholar.msu.edu/enewsletter/volume10/issue2/messina.aspx. Michigan State University.
5. The Engaged Scholar E-Newsletter. 2018. Using satellite data to help communities on the ground. Forster, M. http://research.msu.edu/remote-sensed-data-crop-modeling-helps-African-farmers. Michigan State University.
6. The Oakland Post. 2018. Flying high while also helping communities. Layher, S. https://oaklandpostonline.com/22200/life/flying-high-while-also-helping-communities/. Oakland University.
7. Peter, B. G. 2018. Lansing-Area Data Scientists Group and MSU Social Science Data Analytics Initiative. SSDA social networking event: Data visualization. Panel presentation. Michigan State University.
8. Snapp, S. S. 2018. Farmers and scientists learning to adapt to climate change. Workshop at Tropentag. Ghent, Belgium.

11. Datasets Produced

Dataset	Repository	Notes
Web-based GIS for spatiotemporal crop climate niche mapping	SIII Dataverse	Web-based GIS for spatiotemporal crop climate niche mapping.
Replication Data for: Mapping land suitability for agriculture in Malawi	SIII Dataverse	This remote sensing-based model characterizes land suitability for agriculture in Malawi using a collection of terrain and soil characteristics, including slope, precipitation/runoff/erosion, drainage, sand/silt/clay fraction, soil organic carbon and others.
Multispectral drone imagery of a trial farm in Ntubwi, Malawi	SIII Dataverse	Multispectral imagery collected from an Africa RISING trial site located in Ntubwi, Malawi. Drone flights conducted using a senseFly eBee agricultural-use drone equipped with a Parrot Sequoia camera.

Dataset	Repository	Notes
Multispectral drone imagery of a trial farm in Nyambi, Malawi	SIII Dataverse	Multispectral imagery collected from an Africa RISING trial site located in Nyambi, Malawi. Drone flights conducted using a senseFly eBee agricultural-use drone equipped with a Parrot Sequoia camera.
Replication Data for: Mixed-Method Land Characterizations: Remote Sensing and LULC Survey Data of Malawi	SIII Dataverse	This document contains a crop cover assessment of 200 sites across Malawi and includes responses to inquiries regarding the primary drivers limiting agricultural productivity (based on interviews held with extension planning area officials).
Spatial data outlier detection and visualization using Google Earth Engine	SIII Dataverse	This is associated with an Accepted Manuscript of an article published by IEEE in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing on 20 March 2019.
MODIS product version comparison application for Google Earth Engine	SIII Dataverse	This is associated with an Accepted Manuscript of an article published by IEEE in IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing on 20 March 2019.
Mapping marginal agricultural lands reimagined	SIII Dataverse	This is an adaptation of a model from an Accepted Manuscript of an article published by Taylor & Francis in Annals of the American Association of Geographers on 18 January 2018.
Geovisualizing the modifiable areal unit problem	SIII Dataverse	Geovisualizing the modifiable areal unit problem Interactive Google Earth Engine Application.
Linear workflow for relating multispectral remote sensing imagery with on-farm plant measurements	SIII Dataverse	Linear workflow for relating multispectral remote sensing imagery with on-farm plant measurements.
Visualizing inconsistencies among global agricultural land cover products using Google Earth Engine	SIII Dataverse	This map product demonstrates challenges associated with mapping global agriculture, particularly smallholder agriculture in areas where land use is mixed at fine spatial resolutions (Peter et al. 2018).
Common bean climate niche of Southeastern and Southern Africa	SIII Dataverse	Geospatial dataset of the climate niche for common bean in Southeastern Africa. Temperature and precipitation parameters collected from Beebe et al. (2011).
Growing season temperature variability in Malawi (2016–2017)	SIII Dataverse	This raster structure data set depicts within-season land surface temperature variability trends in Malawi for the 2016–2017 growing season (November–April), categorized based on time-series observations from the NASA MODIS (Moderate Resolution Imaging Spectroradiometer, MOD11A2 V006).
Relating sUAS imagery with on-farm SPAD measurements (PCC, SLR, MLR, and LASSO)	SIII Dataverse-Unpublished	This dataset is relating sUAS imagery with on-farm SPAD measurements.



TANZANIA

East Africa
Tanzania

Raising Crop Response: Bidirectional Learning to Catalyze Sustainable Intensification at Multiple Scales

1. **Lead Institution:** Michigan State University (MSU)
   - International Collaborating Institutions
     - Sokoine University of Agriculture (SUA)
     - Wageningen University
     - CIAT-Tanzania
     - The Nelson Mandela African Institution of Science and Technology (NM-AIST)
     - International Institute of Tropical Agriculture (IITA)

2. **Research Team:**
   - Lead Investigator: Sieglinde Snapp (MSU)
     - Hamisi Tindwa (SUA)
     - Ken Giller (WU)
     - Jean-Claude Rubyogo (CIAT)
     - Neema Kassim (NM-AIST)
     - T.S. Jayne (MSU)
     - Nicole M. Mason (MSU)
     - Mateete Bekunda (IITA ESA)
     - Jordan Chamberlin (CIMMYT) (TAMASA)

3. Executive Summary

Field experiment on lablab maize intercrop and soil sampling final round at SARI. *Photo credit: Sieglinde Snapp.*

We have gained novel insights into the principles and practices involved in sustainable intensification (SI) of rainfed cropping systems on smallholder farms in Tanzania. A key finding is that fertilizer use alone is insufficient, rather it is the SI practices that combine input use with crop diversification, and crop-livestock integration - as indicated by tightening of nutrient cycles - that are associated with child health gains in a nationally representative survey (Jongwoo et al., 2019 Ag. Economics). Fertilizer use alone relative to nil adoption was associated with no gains in children's height-for-age z-score (HAZ) or weight-for-age z-score (WAZ). An agricultural policy that promotes crop diversity and extension of SI knowledge may have multiple and long-term benefits, through greater health as well as income gains documented in a maize-based panel survey of over 600 farmers in Southern and Northern Highlands. In related findings, current extension messaging around crop intensification was found to be highly input-focused, whereas farmers' approach reflected an integrated soil management approach that considered both conservation and fertility objectives. We found that Tanzania agricultural extension and policymakers are aware of such disconnects among researchers-extension-agro traders and the lack of relevance to many farmer priorities and practices, and are actively seeking to better integrate in a dynamic and forward-looking manner; thus our studies were of considerable interest to Tanzania extension.

Extension innovations being explored by Tanzania Ministry of Agriculture include the Village Based Agricultural Advisors (VBAA) model where communities nominate farmers to be VBAAs, who receive extension training and support towards certification as agro-traders. We evaluated this model, providing participatory bidirectional training to hundreds of VBAAs in case study areas, and tested the additional benefit in terms of farmer interest in technologies, through seed packages provided to 1000s of farmers in addition to 'mother' plots that provide an opportunity for VBAAs to demonstrate bean-seed treatments and modern varieties. The proximity of VBAAs to farmers and the personality of VBAA were both found to be related to effectiveness in communicating information about novel SI bean technologies. The benefits of intensified input use, seed treatments with a fungicide and insecticide dressing, and a bean-targeted fertilizer were found to enhance yields by 30 to 100% at 40 sites, reliably, if applied in combination but either alone had uneven benefits. This shows the need for greater attention to integrated SI technologies, to provide farmers with consistent and low-risk gains.

> Overall, in the extension VBAA test, exciting results included that 92% of farmers were made aware of modern varieties and seed treatments and adopters were about one-third.

Sustainable intensification requires attention to how to support natural resource aggradation and conservation in a manner that fits with farmer's interests and priorities. Legume crop diversity and multipurpose legumes, namely pigeon pea and lablab, as shrubby and viney resilient options for soil rehabilitation, forage production, income and nutritious grain all in one integrated technology. Findings included identification of two promising dual-purpose genotypes and three-grain lablab varieties, all as candidates for Tanzania agricultural system release to provide more options for farmers and to support sustainable maize production systems through intercrop and rotations. Overall biomass in a maize-lablab intercrop was substantial, highlighting lablab's high potential in supplementing maize cropping systems. Interestingly, in semi-arid areas, both pigeon pea and lablab provided important options that farmers are actively pursuing, whereas in more mesic, humid areas there was more interest in double or triple cropping beans in rotation with beans. Thus an overall observation emerging from this research project is that an intensive annual legume crop such as bean modern varieties grown with inputs may be most suited to wetter areas, whereas an intercrop of lablab or pigeon pea provides resilience and buffers fertilizer use for SI of maize-based cropping in dryer areas.

4. Project Partners

- Dr. Sieg Snapp, Professor, Michigan State University
- Dr. Hamisi Tindwa, Lecturer, Applied Soil Biology, Sokoine University of Agriculture (SUA)
- Dr. Ken Giller, Professor, Plant Production Systems, Wageningen University (WU)
- Mr. Jean-Claude Rubyogo, Seed Systems Scientist, CIAT-Tanzania
- Dr. Neema Kassim, Department of Food Biotechnology and Nutritional Sciences, The Nelson Mandela African Institution of Science and Technology (NM-AIST)
- Dr. T.S. Jayne, University Foundation Professor, Department of Agricultural, Food and Resource Economics, Michigan State University
- Dr. Nicole M. Mason, Assistant Professor, Department of Agricultural, Food and Resource Economics, Michigan State University
- Dr. Mateete Bekunda, IITA ESA Africa RISING
- Dr. Jordan Chamberlin, CIMMYT Taking Maize to Scale in Africa (TAMASA)

Ngo And Government Partners

- David Priest, Farm Input Promotions Africa
- Neil R. Miller, Agriculture and Livelihoods Technical Advisor Eastern Africa, Canadian Foodgrains Bank and ECHO
- Wilfred Mariki, Tanzania Agriculture Research Institute – Selian Centre, Arusha, Tanzania

5. Project Goals and Objectives

Overall Goal

Feed the Future goals we directly address include: improved agricultural productivity, enhanced human and institutional capacity development for increased sustainable agriculture sector productivity, and improved understanding of how to improve nutritional status, particularly of women and children.

Overall Objectives

Objective 1: To generate improved agronomic knowledge of practices that sustainably raise maize and bean yields and crop response to inorganic fertilizer.

Objective 2: To evaluate forms of bidirectional learning about SI technologies among researchers, extension, agribusiness firms, and farmers in the challenging environment of poorly-resourced agricultural extension programs.

Objective 3: To generate improved knowledge of the nutrition impacts of the adoption of SI technologies and bidirectional learning about those technologies.

Objective 4: To provide practical guidance to governments on staple food marketing, trade and extension policies that support the adoption of SI best practices, to support much broader diffusion and scaling out to millions of farmers, and work synergistically with activities under Obj. 1, 2, and 3.

Feed the Future goals we directly address include: Improved agricultural productivity, enhanced human and institutional capacity development for increased sustainable agriculture sector productivity, and improved understanding of how to improve nutritional status, particularly of women and children.

6. Overview of Activities

Objective 1. Sustainably Raise Maize And Bean Yields

1.1 - Maize-based system survey in partnership with TAMASA

A survey with a household socio-economic component and focal plot with questions covering farmer practices on the plot, plus soil and plant measurements, was conducted during the main maize harvest season in 2016 and 2017. The survey sample area targeted the main maize producing areas in Tanzania while also encompassing a range of soil types. Further detail of the spatial sampling framework had been published earlier as part of the AFSIS and TAMASA approaches. From this sampling procedure, 75 1x1 km grid locations were identified as target areas for the survey. Within each of these grids, a list of all households actively farming land in the grid area was collected and 8 of these households were randomly selected to be surveyed. This resulted in a target of 660 households. The household member interviewed for the survey identified a focal maize plot from which detailed plot management information, soil, and plant samples were collected as described below. The focal plot was defined as the plot within the study grid that the household identified as being most important to their maize production. If a household grew maize on multiple plots within the study grid the focal plot was identified based on economic importance, often determined based on plot size, location, or intensity of production. This survey was conducted as a SIIL partnership with CIMMYT as part of a Taking Maize to Scale in Africa (TAMASA) project, and Tanzania Agriculture Research Institutes. Initial findings include maize response to fertilizer is positively related to soil organic matter status, and farmer perceptions can help inform extension recommendations through the use of the LandPKS App and soil characterization that considers a broader range of soil management practices.

The data sets of both household-level farm practices and socio-economic data and the focal plot soil and plant monitoring have been published in Dataverse and are available both through SIIL and CIMMYT sponsored access.

1.2 - Legume productivity and soil response for sustainable maize-legume systems.
Three field experimentation studies were established and conducted under this objective.

1.2.1 Maize - pigeon pea - lablab intercropping study conducted on-farm.
The Babati district was purposively sampled for setting up experimental trials and three sites/agro-ecological zones (AEZs) (Dareda, Arri and Riroda) were selected. Three farms were randomly selected from each AEZ to host the experimental trials, thus there was a total of nine farms. The trials comprise maize, pigeon pea, and lablab in pure stands and intercrops. Biomass, light interception, and modeling were conducted to quantify the growth of the legume components and to assess soil moisture dynamics to better understand the competition for light and water resources in intercrops, for sustainable design of maize-based farming systems.

Continuous data collection from the experimental trials for the first season has been in progress since January 2018 and the crop that is still in the field (long duration pigeon pea and part of lablab) were harvested end of September/early October 2018. The experiment was repeated in 2019.

Soil and plant monitoring data have been published in Dataverse. One manuscript is in preparation.

1.2.2 Lablab multipurpose legume crop genetic by environment study in Northern Tanzania (Nord, Mariki, Miller, and Snapp)
This study was conducted over the 2016 and 2017 growing seasons at two sites in the Northern Zone of Tanzania, one at the Tanzania Agricultural Research Institute Selian Centre (SARI) located in Arusha and the other at the Tropical Pesticides Research Institute (TPRI) research farm in Miwaleni, Moshi. The experimentalb design of the field trials included two factors, accession, and cropping system, arranged in a modified split-plot with three blocks replicated at each site. The accessions consisted of 14 genotypes chosen based on those that had shown promise from early observations of the full set of accessions, intending to select cultivars with a range of growth types. Four of these accessions were subsequently chosen for further study through on-farm trials to select a final set of accessions for registration. The cropping system factor consisted of each lablab accession sole-cropped or intercropped with maize (Pannar 15). One sole maize plot was also included in each block. Individual plots were 4.5 by 5.4 m with 1.5 m unplanted borders between plots within strips. Lablab spacing was 0.9 m between rows and 0.5 m within rows with five rows per plot and two seeds planted per station (4.4 seeds m-2). Cowpea spacing was half that of lablab, with 0.45 m between rows and 0.5 m within rows. Planting was done in an additive design, where lablab and cowpea spacing was the same intercropped with maize as it was sole cropped. Maize was planted between rows with lablab or cowpea, with six rows per plot at 0.9 m

SIIL researchers visiting trials in Babati, Tanzania. *Photo credit: Ken Giller.*

between rows and 0.5 m within rows and two seeds planted per station for a seeding rate of 4.4 seeds m-2.

Biological nitrogen fixation. Above-ground biomass was sampled from the lablab accessions to quantify biomass yields and sample tissue for 15N analysis. Maize grain yield and lablab pods were hand-harvested and stover and yield determinations made, as well as soil inorganic nitrogen dynamics monitored. Statistical analysis included adaptability analysis as well as three-way ANOVA. Initial findings included identification of two promising dual-purpose genotypes and three-grain lablab varieties, all as candidates for Tanzania agricultural system release to provide more options for farmers and to support sustainable maize production systems through intercrop and rotations. Overall biomass in the intercrop was substantial, highlighting lablab's high potential in supplementing maize cropping systems. Soil and plant monitoring data have been published in Dataverse. A paper has been reviewed favorably at PLOS ONE, and now is in the revision and resubmission process.

1.2.3. Soil monitoring of soil organic matter pools and associated properties to assess the impact of legumes. S. Hamad and H. Tindwa

Taking advantage of three long-term maize-soybean and maize-pigeon pea experiments in Tanzania, the soils were monitored by S. Hamad in continuous maize and maize-legume plots, whereby laboratory analysis of the soil and plant samples collected from the plots in the three sites aimed at finding out whether or not intercrops and or rotations involving legumes such as soybeans have contributions on C-pools in agricultural soils. Further, variations in SOC especially the water-extractable SOC portion along with N in addition to biomass accumulations that can directly be attributed to N-fixation by the soybean in the system are being assessed. The student is also assessing the aggregate stability of the soils as impacted by varying levels of SOC in the various treatments. Pedological and fertility characterizations of all the three sites have also been done as part of objective one of this Ph.D. study.

Objective 2. Extension Approaches: To Evaluate Forms Of Bidirectional Learning About Si Technologies

Promising maize-bean system technologies were evaluated in the context of this study to quantify the effects of greater participation of farmers in extension. Specifically, a study was carried out in the southern highlands of Tanzania to test: (1) The effect of quality seed of improved varieties and complementary inputs on bean yield. (2) Whether if the use of APRON STAR 42 WS - dressed bean seeds is economically viable for commercialization and choice recommendation to improve the livelihoods of smallholder farmers in Mbeya rural and Mbozi districts. (3) Comparing the mother trials versus mother + baby trials impacts bidirectional learning and input sales, farmer use, and willingness-to-pay across the seven districts. (4) If different extension approaches affect smallholder farmers' willingness-to-pay for new agricultural technologies in Mbeya rural and Mbozi districts. (5) Assessing the effectiveness of lead-farmer extension (the role of personality and physical distance).

The linkages among extension advisors, researchers, and farmers' interests and challenges faced in soil erosion control, soil health and soil fertility management were explored through a novel LandPKS App, and mixed methods to interview farmers and extension advisors. Farmers' practices were found to be associated with both soil conservation and fertility management, whereas extension advice focused primarily on inputs and fertilizer use. Further, the extension advisor knowledge 'ecosystem' was documented, and linkages to private-public actors and degree training at extension colleges, with little or no feedback with researchers and modest interaction with farmer's practices. These findings are being synthesized, with an initial manuscript that has been reviewed favorably at Land Degradation and Development, and this study is in the revision and resubmission process.

Initial findings have been presented in Tanzania for feedback and interaction with government and NGO partnerships for more effective extension:

- Biedny, C., N. Mason, S. Snapp, A. Nord, J.C. Rubyogo, and J. Lwehabura. 2019. "Bean mother demos vs. mother + baby demos impacts on bidirectional learning and input sales, farmer use, and willingness-to-pay: Evidence from Tanzania." Presentation at the Final Outreach Workshop for SIIL Tanzania. Mbeya, Tanzania. Aug. 29, 2019.
- Morgan, S, N. Mason, and M. Maredia. 2019. "Do different extension approaches affect smallholder farmers' willingness-to-pay for new agricultural technologies? Experimental auction results from Tanzania." Presentation at the Final Outreach Workshop for SIIL Tanzania. Mbeya, Tanzania. Aug. 29, 2019. §
- Farris, J., M. Maredia, N. Mason, and D. Ortega. 2019. "Effectiveness of lead-farmer extension in Tanzania: The role of personality and physical distance." Presentation at the Final Outreach Workshop for SIIL Tanzania. Mbeya, Tanzania. Aug. 29, 2019. §
- Farris, J., M. Maredia, N. Mason, and D. Ortega. 2019. "Effectiveness of lead-farmer extension in Tanzania: The role of personality and physical distance." Selected paper presented at the Agricultural & Applied Economics Association's annual meeting. Atlanta, GA. Jul. 22, 2019. §
- Morgan, S., N. Mason, and M. Maredia. 2019. "Farmer-led extension and smallholder valuation of new agricultural technologies in Tanzania." Selected paper presented at the 16th Midwest International Economic Development Conference, Pyle Center, University of Wisconsin-Madison. Madison, WI. April 27, 2019

Final Outreach Workshop for SIIL Tanzania. Mbeya, Tanzania. Aug. 29, 2019.

Objective 3. To Generate Improved Knowledge Of The Nutrition Impacts Of Adoption Of Si Technologies.

Assessing soil health and color. Photo credit: Alison Nord.

Using nationally representative survey data, a seminal study was conducted to estimate the effects of SI of maize production on the child nutrition outcomes of maize-growing households in Tanzania. The focus was on maize due to its importance as a staple food in Tanzania and because it accounts for approximately 75% of the total cropped area in the country. These surveys were conducted by the TNBS in conjunction with the World Bank. The statistical approach included a multinomial endogenous treatment effects (METE) model combined with the correlated random effects (CRE) approach using three-waves of this nationally representative household panel survey data (the Tanzania National Panel Surveys of 2008/09, 2010/11, and 2012/13).

Findings (published in the high impact journal Agricultural Economics):

- Three soil fertility management practices (inorganic fertilizer, organic fertilizer, and maize-legume intercropping) used by rural Tanzanian households on their maize plots influenced nutritional outcomes of children aged 6-59 months within the household.
- The results suggest that joint use of inorganic fertilizer with maize-legume intercropping and/or organic fertilizer (which we refer to as the sustainable intensification or SI group of practices) is associated with increases in children's height-for-age z-score (HAZ) and weight-for-age z-score (WAZ) compared to households that adopt none of the practices.
- The positive effects of the SI group are mainly among children aged 25-59 months who, compared to younger children, are less likely to be breastfed and may be more directly affected by household diet changes associated with changes in agricultural practices.

- Joint use of maize-legume intercropping and inorganic fertilizer is a key driver of the positive SI effects, and the effects appear to come through both crop income and productivity pathways.
- On the other hand, the use of only inorganic fertilizer (Intensification) and the use of only Sustainable practices (only organic fertilizer, only maize-legume intercropping, or both) have no statistically significant effects on the HAZ and WAZ of children age 25-59 months.

Objective 4. Practical Guidance To Governments On Staple Food Marketing, Trade And Extension Policies

Maize export policies and pricing do influence farmers' profitable adoption of SI technologies, this guidance work is underway and in the final stages.

7. Accomplishments

Long-Term Training Graduate Students

Nord, Alison (August 1, 2015 to December 31, 2019) Scheduled Ph.D. defense November 22, 2019
Mugi, Esther (August 1, 2016 to June 1, 2020) In Progress
Hamad, Said (June 1, 2016 to December 1, 2020) In Progress
Fredrick, Rufina (October 9, 2017 to May 4, 2020) In Progress

Short-Term Training

Conducted trainings with more than 200 lead farmers and extension advisors over multiple time points, as part of objective 2.?

8. Utilization of Research Outputs

Bean Seed Treatment (Apron Star 42 Ws) For Healthy Disease And Insect Resistant Growth Of Bean For Higher Yields

Among the over 300 farmers who evaluated the technology, yields were quantified on 60 fields and found to be modestly higher with seed treatment and substantially higher with the combination of seed treatment with basal fertilizer. About one-third of farmers have since requested access to the seed treatment for implementation on bean production fields, so a significant interest in use particularly among farmers who were exposed to the technology through mother and baby demos with village-based advisors (VBAAs).

Bean Modern Varieties

Among the over 300 farmers who evaluated the technology, yields were quantified on 60 fields and found to vary by site, overall a modest increase in yield among modern varieties vs conventional varieties but this did not hold for all sites. Farmer's interest in modern varieties varied by site as well.

Lab Lab Variety Release

Four varieties of Lablab are now in the final stages of on-farm testing for government release in 2020.

SI Agricultural And Extension Findings And Policy Implications

Key issues regarding the adoption and impact of seed treatment (APRON STAR 42 WS) on farmers' livelihood:

- The study used a sample size of 203 farm households to analyze the adoption and impact of Apron Star 42 WS dressed bean seeds in Mbeya Rural and Mbozi districts. All farmers who happened to willingly buy the seeds from Agro- dealers and/or VBAAs in the 2018/19 season were termed as adopters and the vice versa.

- o It was reported that the majority (92%) of farmers are aware of the "seeds" and seed treatments and adopters were about 37%.

Sources of information about the seeds as mentioned by farmers were the village-based advisors, the VBAAs. There was also information being provided by NGOs and researchers, including One Acre Fund Programme, CIAT, Beula Seed Company, friends, agro-dealers and extension officers. For the majority of adopters, the primary source of information was VBAAs.

9. Future Challenges and Opportunities

Tanzania agricultural extension and policymakers are aware of disconnects among researchers-extension-agro-traders, where extension staff is not given new research update information and the lack of relevance of some extension recommendations to farmer systems. That is, fertilizer and crop spacing recommendations are often given without regard to farmer's practices, or to market-orientation. For example, pigeon pea recommendations are focused on sole-crops, whereas farmers grow pigeon pea in maize intercrops, and have a range of goals from market to local use of some pigeon pea products (fuelwood, fodder and green vegetable pods). Research priorities, extension recommendations, and policy would be of greater relevance if a systems, bi-directional approach was undertaken that engaged with farmers and considered integrated and livelihoods approach – e.g., farmers often have crops they are growing for market, while others are for local use and innovations need to reflect the need for both.

There is considerable interest in our findings on how to enhance extension extend the reach and relevance, of extension through supporting VBAA local advisors. There is considerable interest as well in the use of IT innovative Apps such as the LandPKS soil management App which we explored here. The next steps could include training of VBAAs in using the LandPKS to reach more farmers and to enhance the effectiveness of VBAAs.

The importance of extension is reinforced by our findings regarding the need for sustainable technologies to be integrated with fertilizers as the later is being promoted with limited attention to the former, which tend to be much more knowledge-intensive and thus requires extension practices that engage with farmers.

A way forward would be to work with Tanzania agricultural research and extension to support better addressing of marginal areas, where the need is clear for multipurpose legume crops, as well as to mesic areas where bean and related intensified seed-based technologies are underway and currently being adopted. Thus a shift to focus less on maize fertilizers based interventions alone would allow resources to be invested in SI and integrated technologies, both biological and economic. Further, practical guidance to governments on staple food marketing, trade, and extension policies is urgently needed, and this SI project highlighted the need to consider the often indirect and long-term effects, such as those documented here. SI technology affirming policies are needed, that consider not just input use alone, but sustainable complementary practices to support child health, as well as farmer ability to adapt to a variable climate and dynamic markets, particularly in marginal areas.

10. Publications

1. Jongwoo K., N.M. Mason, S.S. Snapp, and F. Wu. 2019. Does sustainable intensification of maize production enhance child nutrition? Evidence from rural Tanzania. Agricultural Economics, in press.
2. Mugi, E. and others, manuscript in preparation. Farm-level agronomic survey for an in-depth understanding of farming systems and evaluation of suitability of maize-legume intercropping in Northern Tanzania
3. Chamberlin, Jayne and others, 'Maize response to fertilizer as conditioned by soil organic matter'. This is in preparation.

4. Nord and Snapp, in the review. 'Documentation of Farmer Perceptions and Site-Specific Properties to Improve Soil Management on Smallholder Farms' Submitted to Land Degradation and Development.
5. Nord et al. manuscript in review with PLOS ONE on 'Investigating the diverse potential of a multi-purpose legume, Lablab purpureus (L.) Sweet, for smallholder production in East Africa'
6. Nord et al. manuscript is in preparation. Legume Management vs. Recommendations: Disconnection between Agricultural Extension and Farmer Legume Management Illustrates Complexity of Legume Production
7. Jongwoo et al., in preparation. The impacts of sustainable intensification of maize production on crop income and productivity: Evidence from rural Tanzania
8. Biedny C., N. Mason, S. Snapp, J.C. Rubyogo, J. Lwehabura, and *A. Nord. "Demonstration plots, seed trial packs, bidirectional learning, and modern input sales: Evidence from a field experiment in Tanzania." Manuscript in preparation
9. J. Farris, M. Maredia, N. Mason, and D. Ortega. "Effectiveness of lead-farmer extension in Tanzania: The Role of Personality and Physical Distance" Manuscript in preparation

Policy Papers And Input

- Kim J., N. Mason, S. Snapp, and F. Wu. 2019. "Does sustainable intensification of maize production enhance child nutrition? Evidence from rural Tanzania." Policy brief. Feed the Future Innovation Lab for Collaborative Research on Sustainable Intensification. August 2019.

11. Datasets Produced

Dataset	Repository	Notes
Evaluation of technologies through onfarm bean mother demos	SIIL Dataverse	This dataset contains raw and extrapolated yield data from on farm mother demos of beans for evaluating performance of technologies in Southern Highlands of Tanzania.
Soil samples collected and analysed using soil doc and dry chemsitry to compare the results	SIIL Dataverse	These datasets contained analyzed soil samples using two methods, named soil doc and dry chemistry to compare and improve the results.
On farm evaluation of best bet lablab accessions for certified seed release in Tanzania	SIIL Dataverse	This is a dataset with two files to support the requirements of on farm evaluation of best bet lablab accessions for certified seed release in Tanzania.
Technology and bean performance assessment	SIIL Dataverse	These datasets contained technology and plant performance assessment for mother demos established in 2017 in Southern highlands of Tanzania.
Lablab Genotype and Cropping System Experiment	SIIL Dataverse	This dataset includes raw data from a field trial evaluating lablab accessions in northern Tanzania. The trial was conducted at two

Dataset	Repository	Notes
		sites in northern Tanzania and data was collected in 2016 and 2017.
Tanzania Southern Highlands Village-Based Agricultural Advisors Baseline Survey	SIIL Dataverse	This data set contains baseline survey data from 216 active Village-Based Agricultural Advisors (VBAAs) associated with Farm Input Promotions-Africa operating in seven districts in the Southern Highlands of Tanzania.
Tanzania Southern Highlands Village-Based Agricultural Advisors Endline Survey	SIIL Dataverse	This data set contains endline survey data from interviews with 193 Village-Based Agricultural Advisors (VBAAs) associated with Farm Input Promotions-Africa operating in seven districts in the Southern Highlands of Tanzania.
Maize/ legume intercrops	SIIL Dataverse-Unpublished	This dataset includes raw data from experimental trial evaluating performance of maize/ legume systems in Babati, northern Tanzania. The trial was conducted in three sites, with three farms per site, following a one farm-one replicate design.
Tanzania National Panel Surveys of 2008/09, 2010/11, and 2012/13	Public Access	Tanzania National Panel Surveys available to the public.

BANGLADESH

Bangladesh

Unlocking the Production Potential of "Polder Communities" in Coastal Bangladesh through Improved Resource Use Efficiency and Diversified Cropping Systems

1. **Lead Institution:** Kansas State University
   - International Collaborating Institutions:
     - International Rice Research Institute (IRRI-Bangladesh)
     - BRAC
     - Khulna University

2. **Research Team:**
   - Lead Investigator:
     - Krishna Jagadish (KSU)
   - Co-Investigators:
     - Sudhir Yadav, IRRI

3. Executive Summary

The coastal zone of Bangladesh is one of the most climate-vulnerable regions of the world, but is rich with water resources. The rivers are tidal; high and low tides occur twice daily that offer irrigation and drainage by gravity. The government of Bangladesh constructed 139 polders during the 1960s-70s to protect 1.2 Mha low-lying lands from tidal flooding and salinity intrusion for increasing agricultural productivity and improving the livelihood of the communities. Despite this huge investment, the productivity in the polders is still low, much lower than in other parts of Bangladesh. Our studies in a medium-saline polder 30 from October 2015 to September 2019 showed that land productivity can be significantly improved through integrated water management and synchronized cropping involving the community. The key findings of the project are highlighted below:

Paddy harvesting operations were done by using mini combine harvester and ACL reaper at Kalapara, Patuakhali, Hangladesh. *Photo credit: Kamrul Hasan.*

- Developed two most productive, profitable and resilient cropping patterns through innovative community-led water management (hydrologically-bounded community, not geographically-bounded) matching with the polder agro-hydrology with 2-3 times higher productivity than the farmers' cropping practices (av. of 3 years 3.0-3.4 t/ha/yr.).

- Developed women entrepreneurs in agricultural mechanization; the landless poor who used to harvest paddy manually are now providing services to the community by harvesting paddy using reaper and leading improved livelihoods with higher (USD 392-503 per year) income than before (USD 45-114 per year).

- Capacity building of about 7000 farming community (~50% women) and 14 next-generation local scientists and professionals (36% women) on different aspects of crop and water management under polder environment, marketing and trade-off among new crops and cropping systems with the traditional cropping. They are expected to contribute to future challenges in the food and nutritional security of the coastal communities of Bangladesh.

- Introduction of biofortified zinc rice, sunflower and maize are expected to improve household nutrition. Sunflower, as a dry season crop, is gaining popularity not only for its resilience but also its high acceptance as edible oil generated from the farmer's farm. The community used maize grains and leaves as the feed for their poultry, livestock, and fish through which the household had more access to milk, meat, egg and fish that helped improve the nutrition of the polder communities.

- The learning hub model could be an appropriate agricultural technology dissemination model for cropping intensification in the polders of the coastal zone of Bangladesh.

- Shared the learnings of the project through the peer-reviewed journals; strategic communications/blogs, and through conferences and meetings

- Established knowledge-sharing platform to bring together key actors of the many current agricultural cropping systems, water management, aquaculture, mechanization, and ICT R4D projects active in the polders of the coastal zone of Bangladesh to share knowledge, information and ideas from different development projects and to improve networking across these initiatives

> By adoption of improved rice-based production systems through intelligent management of tidal river water resources of the coastal zone, Bangladesh could make a quantum leap in meeting future food security requirements and in achieving SDG1 and SDG2 within 2030.

Bangladesh faces enormous challenges to maintain food sufficiency due to natural calamities and population growth of 1.2% per year. There is little scope to further increase food production, except the underutilized 1.2 Mha area in the polders of the coastal zone of Bangladesh.

4. Project Partners

Kansas State University and the International Rice Research Institute jointly implemented the project in partnership with BRAC and local universities (non-binding partners). The local universities that the project was engaged through postgraduate students were:

- Bangladesh Agricultural University
- Sher-e-Bangla Agricultural University
- Patuakhali Science and Technology University
- Khulna University
- University of Arkansas

Among them, the two universities are located in the coastal zone of Bangladesh. The project also worked with the government (Bangladesh Agricultural Research Council, Bangladesh Water Development Board, Department of Agricultural Extension, Institute of Water Modeling) and nongovernment (BRAC) organizations working in the field of water resources management and agricultural development; the agencies provided an advisory role during the implementation of the project.

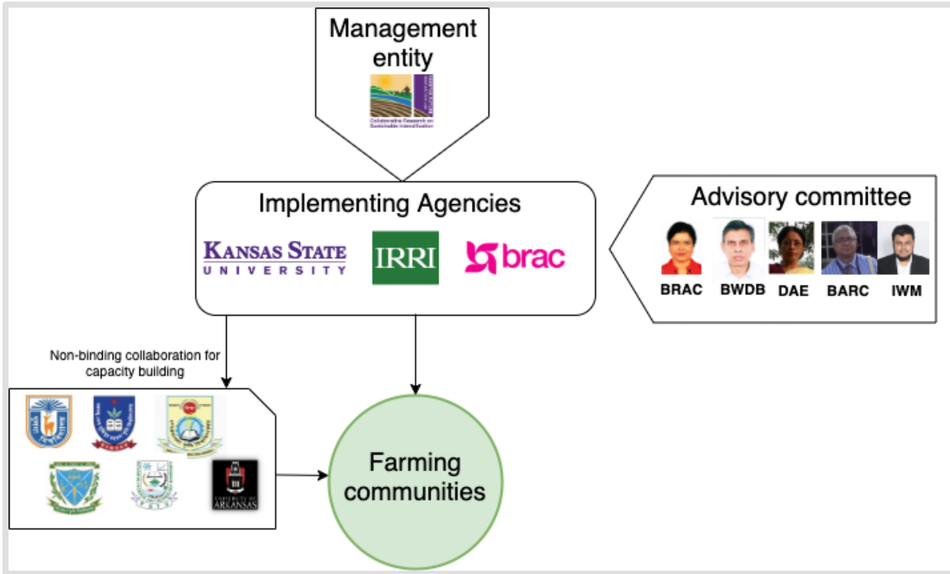


Figure 1. Project governance structure.

5. Project Goals and Objectives

Overall Goal

The overall project goal was to plan, evaluate and support the adoption of pragmatic farming approaches for the efficient use of available natural and human resources to improve food security, human nutrition, and livelihoods of rural polder communities in southern Bangladesh.

Overall Objectives

The specific objectives were:

Objective 1: Devise and evaluate options to increase cropping intensity and farm productivity by making the best use of available resources and the introduction of mechanization.

Objective 2: Introduce and evaluate opportunities for farm diversification to enhance human nutritional security and provide alternative sources of feed for livestock.

Objective 3: Introduce new income-generating opportunities for poor women and landless farmers.

Objective 4: Perform a socioeconomic assessment of the introduced technologies, including costs and returns, farmers' perceptions, barriers to adoption, adoption potential, and impact on vulnerable groups (poor, landless farmers, and women.

Objective 5: Assess the triple bottom line sustainability (social, economic, and environmental dimensions) of the farming system changes introduced under current and future scenarios (as affected by climate change, investments in development, and rural migration).

Objective 6: Enhance institutional, extension and research capacity building.

Objective 7: Upscale and outscale successful farming technologies.

Project Site

The study was conducted at 10 learning hubs (LH) in polder 30 located in Ganges Tidal Floodplain agro-ecological zone in south-west Bangladesh (Figure 2). The total area of the polder is about 70 km^2. The land within the polder is protected from high tides by an embankment 40 km long and 4.3 meters wide at the crest. The polder is surrounded by five rivers, of which two major rivers, namely the Kazibacha and Lower Salta, are on the east and west sides, respectively. The rivers are tidal, with water levels varying by about 4 m between low and high tide (Khan et al. 2015). There are 21 sluice gates in the embankment which connect the internal canal network to the surrounding rivers. Also, there are 6 inlets (flushing gates) at the land surface level in higher locations for irrigation by overland flooding (CEGIS 2015). The sluice and flushing gates allow the inflow of water into the polder during high tide, and for drainage into the river *via* the sluice gates during low tide. A total of 53 canals exist in the polder with a total length of about 107 km (Mondal et al. 2010).

The water salinity in the peripheral rivers of polder 30 remains below 1 dS m^{-1} from July to December and gradually increases to a peak of 15-20 dS m^{-1} in April-May (SRDI 2014; Mondal et al. 2006). The soils are mostly silty clay to at least a meter depth (Ritu et al. 2015). Salinity (electrical conductivity of the saturation extract) of the topsoil (0–15 cm) varies from 2-4 dS m^{-1} at the end of the rainy season to 7-14 dS m^{-1} towards the end of the dry season (Mondal et al. 2006). Currently, polder 30 is considered to be a medium salinity region, but the salinity gradient is predicted to encroach inland over the coming decades (Khan et al. 2015; Mahmuduzzaman et al. 2014).

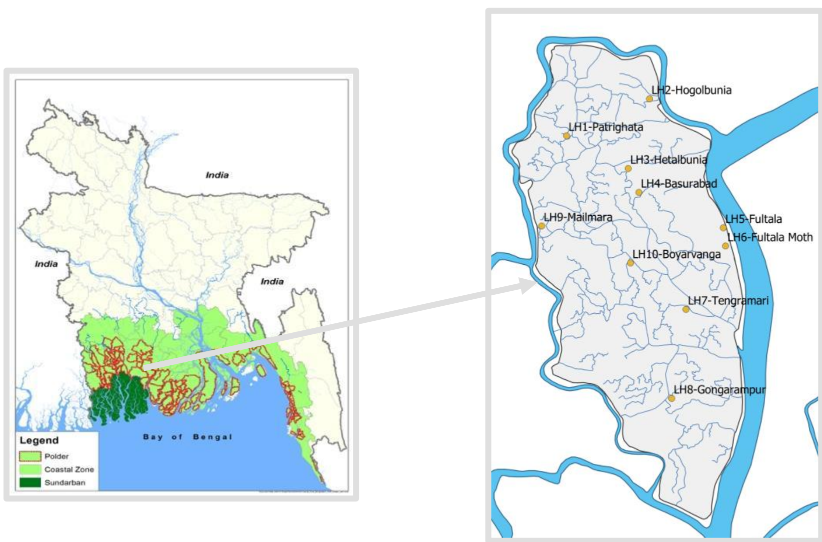


Figure 2. Map of polder 30 showing the 10 learning hubs of the SIIL-Polder Project.

6. Overview of Activities & Accomplishments

Objective 1: Increase Cropping Intensity And Farm Productivity

1.1 - Introduced high yielding climate-resilient and nutritious rice varieties in the wet season

Historically, the farmers in the polder ecosystem cultivate single traditional rice in the wet season (popularly known as *aman* season), sometimes followed by traditional mungbean and sesame in the dry season (popularly known as *rabi* season). But the *rabi* crops are often damaged by pre-monsoon rains and cyclones at or near maturity mainly due to late establishment. The main reason for the late establishment is the adoption of long duration *aman* rice and inappropriate water management, especially late terminal drainage in the latter part of December that delay drying of soil optimum for *rabi* crop establishment. We, therefore, introduced short-duration high yielding varieties (HYVs) of *aman* rice with improved water management to increase year-round land productivity judiciously utilizing available water resources.

Adaptive trials on climate-resilient (BRRI dhan52 with sub1 gene) and nutritious (BRRI dhan72, zinc biofortified) HYV rice with a more strategic approach in using learning hubs (LH) were conducted in the aman seasons of 2016, 2017 and 2018. The LHs lies within the catchment area of seven regulators in polder 30. Along with improving climate resilience, the project targeted to improve nutrition especially among children and lactating mothers by including nutritious rice in demonstrations. As the farmers had limited experience on HYV rice cultivation, the project distributed good quality seeds of the HYV rice and provided training to the farmers and members of water management organizations (WMOs) of ten LHs. They were mentored throughout the project period to upgrade their knowledge and skills on synchronized cropping with improved water management. The performance of the introduced rice varieties was much better than the traditional varieties cultivated by the farmers (Figure 3). The mean grain yield of the HYVs (4.7 t/ha) was ~2.0 t/ha higher than the traditional rice, indicating more food availability among the LH households. In general, the yield of rice was higher in 2018 compared to the previous seasons (2016 and 2017) mainly due to enhanced knowledge of the farmers and WMOs on synchronized cropping with polder water management. Therefore, the introduction of HYV rice increased the wet season productivity by ~ 2 t/ha over traditional farmers' cropping, clearly indicating potentials of the polder zone to sustain food security of the nation.

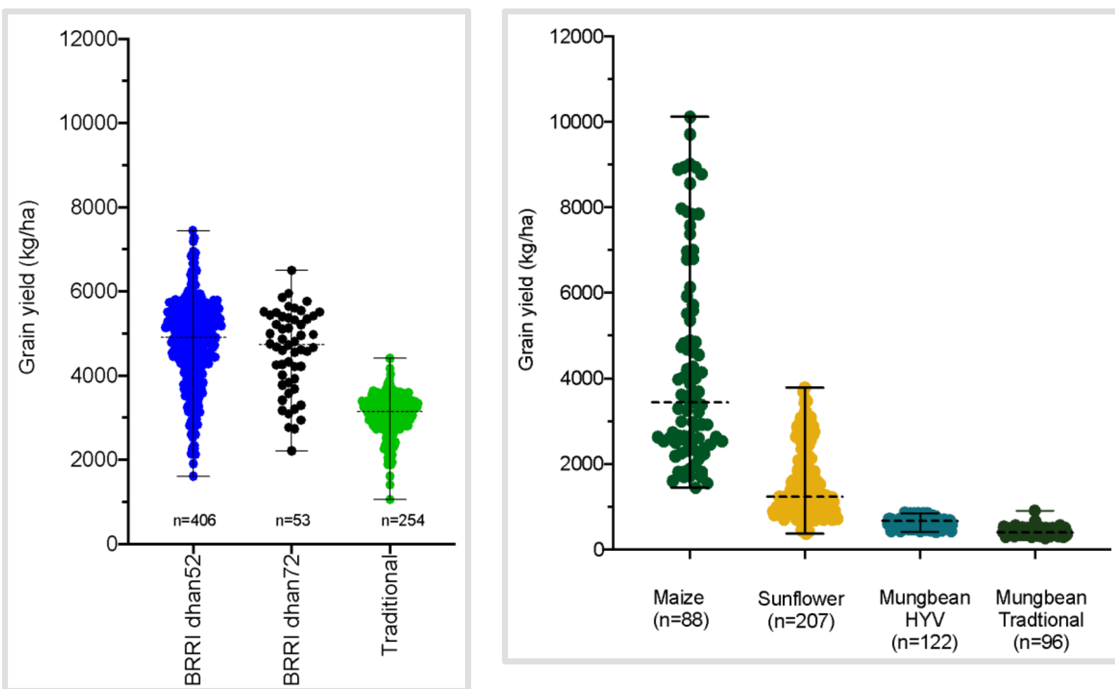


Figure 3. Mean grain yield (mean of three years) of high yielding and traditional rice varieties and dry season crops in polder 30.

1.2 - Introduced high yielding, high-value, and nutritious *rabi* crops in the dry season

The project has created an enabling environment for the early establishment of *rabi* crops by introducing HYV rice (shorter growth duration than traditional rice) in *aman* season and empowering WMOs (WMG - water management group, WMA - water management association) for improving water governance through timely (after physiological maturity of HYV rice) drainage of ponding water from the polder lands. As the river water becomes saline (not suitable for crop irrigation), the growth and development of the *rabi* crops depend mainly on rainfall and how best the residual soil water is utilized. Hands-on training of the WMO personnel and the LH farmers were therefore provided on the residual soil water utilization and cultivation procedure of *rabi* crops, and their importance on health and human nutrition; the importance of early crop establishment for better yield and safe harvest of *rabi* crops to encourage the farmers to cultivate high value and nutritious *rabi* crops in the dry season.

Since the dry season crops cultivated by the farmers (mungbean and sesame) are often damaged by pre-monsoon rains before harvest due to late establishment, the project introduced HYV of maize, mungbean, and sunflower not only to increased land productivity but also to improve household nutrition. Introduction of maize (av. 4.2 t/ha), and sunflower (av. 1.5 t/ha) increased land productivity in the dry season over the farmers' practice (av. yield of traditional mungbean was 0.42 t/ha) and the crops showed better resilience and produced at least a breakeven yield under stressed environment (drought) in 2017-18 (Figures 4).

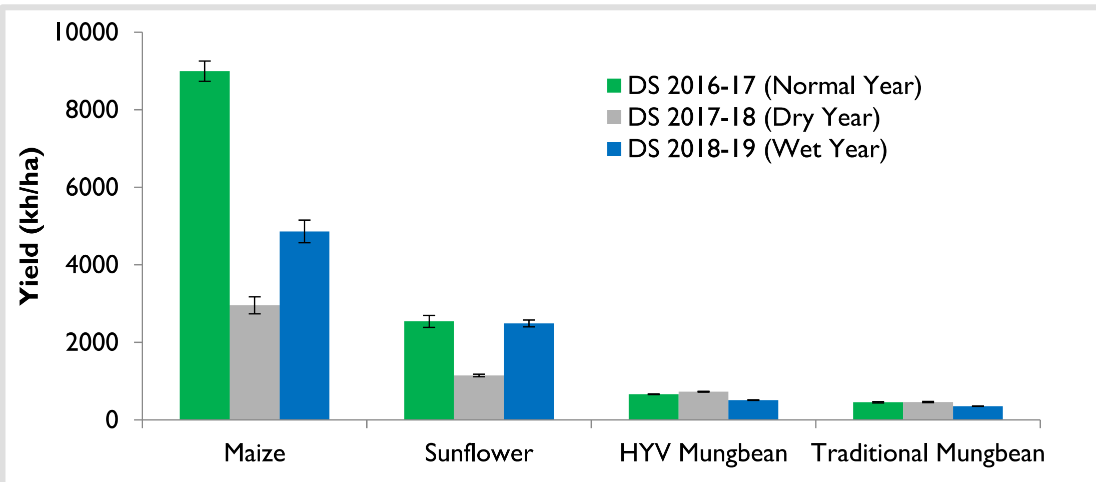


Figure 4. Grain yield of maize, mungbean, and sunflower in the normal, dry and wet years (depending on rainfall).

In the normal year (2016-17), maize (9 t/ha) and sunflower (2.5 t/ha) produced much higher than wet and dry years due to uniform distribution of 56-98 mm rainfall per month from March to May. But the yield was drastically reduced (maize - 3 t/ha and sunflower - 1.1 t/ha) in the dry year (2017-18) with no rainfall event from mid-December to March and the growth of maize and sunflower was stunted. In the wet year (2018-19), about 100 mm rainfall occurred in every month after crop establishment (from February to May). As a result, most of the rabi crops were damaged due to waterlogging after crop emergence (172 mm rain occurred over four days in February 2019). But the crops cultivated near the drainage canals survived and produced a much higher yield than a dry year (2017-18), except mungbean that performed well under drought than wet (in many cases, farmers had re-sown when the first sowing damaged) environment.

1.3 - Developed nutrient management in rice under the polder ecosystem

In the polder ecosystem, a significant amount of silt enters inside the polder through the tidal river water that may contribute to soil fertility. We, therefore, conducted a study to document the performance of HYVs under different fertilizer management and compared them with traditional varieties. The tested HYVs produced a significantly higher yield than the traditional variety with all tested levels of fertilizer, including no fertilizer. The HYVs produced similar yield at 100% recommended fertilizer, 100%N+50%PKSZn, and 50% N+50% PKSZn of the recommended dose. Based on the experimental performance of HYV rice with different fertilizer management in 2016 and

2017, large scale field trials in the LHs at 100%N+50%PKSZn and 50% N+50% PKSZn fertilizer doses were conducted in 2018 aman season. The farmers who cultivated BRRI dhan52 with 100% recommended N and 50% of recommended P, K, S, and Zn harvested 5.3 t/ha, which was about 19% higher than those who used 50% of the recommended fertilizer. (Figure 5). The study showed that a significant amount of chemical fertilizer can be saved for rice cultivation in the polder ecosystem that might positively contribute to reducing environmental footprints.

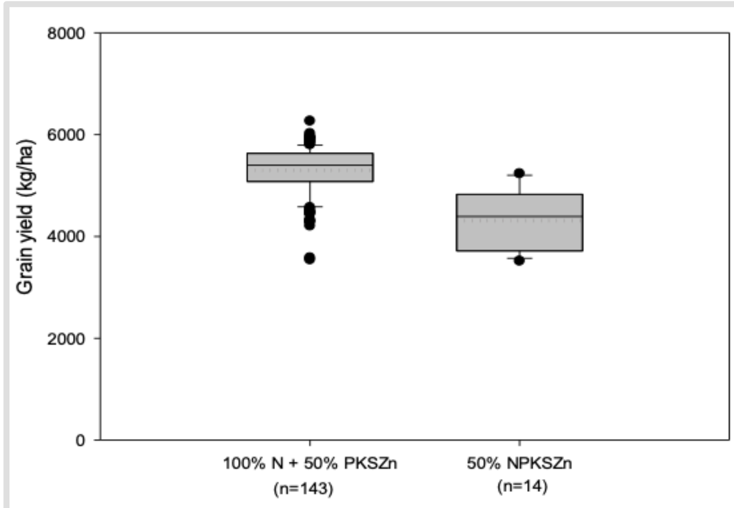


Figure 5. Yield of BRRI dhan52 in aman season 2018 obtained from a large-scale demonstration under different fertilizer management.

1.4 - Awareness building on mechanical establishment of rice and *rabi* crops

Land preparation is fully mechanized in Bangladesh including in the polders of the coastal zone of Bangladesh. However, all other agricultural activities are generally done manually. As part of awareness building, the project introduced the rice transplanter, reaper, power tiller operated seeded (PTOS), battery-operated sprayer, and axial flow pump to popularize agricultural mechanization among the polder communities.

The project empowered the community on the use of rice transplanter, and format nursery preparation required for the transplanter. The project conducted 18 demonstrations at 10 sites in polder 30 on use of the transplanter involving the farmers, representatives of the WMOs, local leaders and GO-NGO officials. Although machine transplanting (MT) was faster and economical than hand transplanting (HT), its use was limited due to the cultivation of traditional rice varieties in the polders (seedlings of traditional varieties were tall at the time of planting, therefore, got damaged in machine transplanter). The project also introduced and demonstrated the performance of battery-operated sprayer for safe application of pesticides in both rice and *rabi* crops (29 times at 9 sites), axial flow pump for cost-effective pumping for irrigation and drainage (only once), PTOS for sowing seeds of *rabi* crops (7 times at 5 sites), and use of a mini 2-wheel tractor to pulverize topsoil in between two rows established by dibbling on moist soil to address the adverse effects of soil cracking on the growth of *rabi* crop and subsequent fertilizer management for higher yield (3 times at 2 sites). The community expressed that the project has taken a very good initiative to sustain future agriculture.

Objective 2: Farm Diversification

The project has introduced rice-based cropping patterns including integrated rice+fish cultivation in the wet season and introduced dry season crops to enhance household nutrition and alternate sources of feed for the livestock and fish.

2.1 - Evaluating opportunities for farm diversification

The major cropping patterns in polder 30 were Traditional Rice-Fallow and Traditional Rice-Traditional Mungbean/Sesame. Through improved water management involving the community, the project has developed three improved cropping patterns suitable for the medium-saline polder environment. Among them, HYV Rice-Maize was the most productive (4.9-18.9 t/ha/yr.) cropping pattern, followed by HYV Rice-Sunflower (3.9-14.5 t/ha) and HYV Rice-HYV Mungbean (3.3-8.7 t/ha), productivity was 2-3 times higher than farmers' cropping practice under different climatic conditions i.e., in normal, dry and wet years (Figure 6). Like productivity, the net income from the improved cropping patterns varied depending on the prevailing climatic conditions. Under drought in the dry season, HYV Rice-HYV Mungbean (net income $759/ha/yr.) was the most profitable cropping pattern, followed by HYV Rice-Sunflower ($539/ha/yr.) and HYV Rice-Maize ($527/ha/yr.), net income 1-45% higher than farmers' practice. However, in the normal year, HYV Rice-Maize (about 3 times farmers' practice) and wet year HYV Rice-Sunflower (about double than farmers' practice) had higher profitability.

Improved cropping patterns showed better climate-resilience, produced at least two-times higher yield but with more fertilizer and pesticides than the traditional farmers' practice. The new cropping patterns have the potential to address the food security challenges of Bangladesh; still, social cohesion inclines towards traditional cropping practices, as the majority of farmers cultivate traditional crops in wet and dry seasons due to lack of knowledge and inappropriate water management and governance in the polders of the coastal zone of Bangladesh.

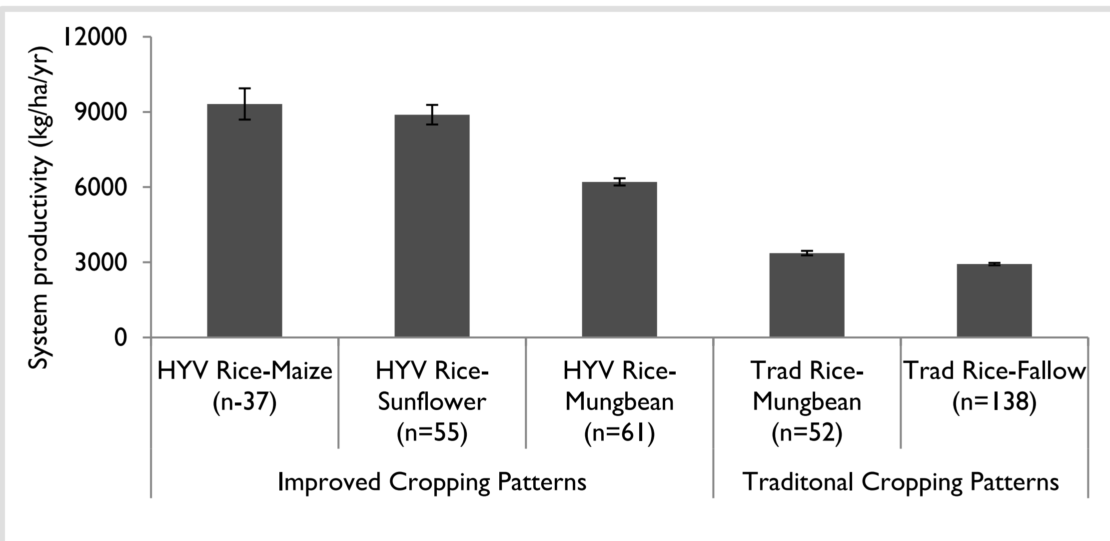


Figure 6. System productivity (REY) of improved cropping and traditional cropping patterns.

2.2 - Use of maize and sunflower for food and feed for livestock

The project is also exploring potential crops, such as maize in the dry season, not only to contribute to food security or income for the farming community but also as an alternative feed for livestock, poultry, and fish grown in homestead ponds. To achieve this goal, the project has provided training to the LH farmers on nutritional aspects of maize for human consumption directly and via the animal product (milk, meat, egg, and fish); and of sunflower oil and pulses. The farmers who cultivated maize mostly used the grains to feed their poultry, livestock, and fish cultured in domestic ponds; and used maize leaves to feed their livestock. The farmers reported increased production and consumption of milk, meat, egg, and fish due to feeding the livestock and fish with maize. The farmers also reported that they have started consuming sunflower oil crushing the seeds from local crushing mills. An intake of additional production is expected to improve household nutrition.

2.3. - Opportunities for integrated rice-fish culture in the polder ecosystem for improving household nutrition and income

Integrated rice+fish culture in the polder ecosystems was conducted to improve the livelihood and nutritional security of the polder communities. The community model was tested for the rice-fish demonstration in LH5: Fultala in the *aman* season (Figure 7). The area of the rice-fish watershed is about 6 ha, having a small canal (about 500 m) and nine small ditches inside the watershed, where fish took shelter during fertilizer and pesticide application in rice and even after the rice harvest. The community consisted of 44 households, of which 28 have landed inside the watershed, and the rest are either landless (7 HHs) or have land outside the watershed (9 HHs). The family composition was made up of 5% children (less than five years old) and 14% aged between 6 to 15 years, and 30% less than 36 years indicating half of the community was of young age.

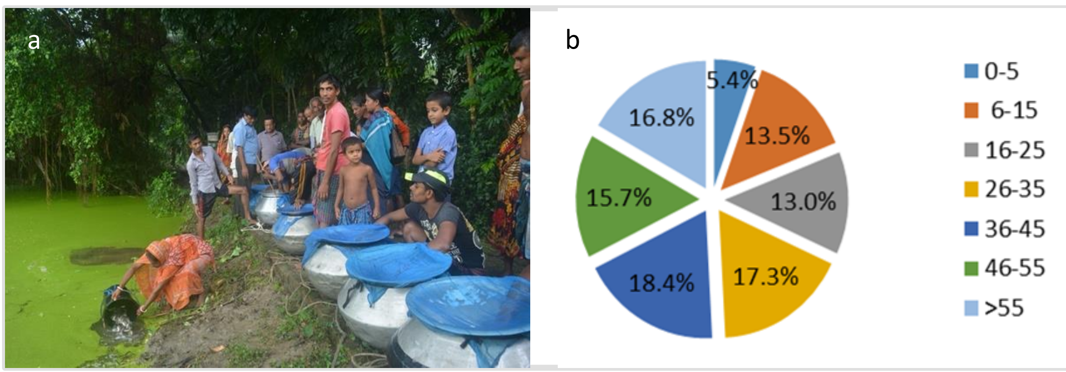


Figure 7. Community (a) rice+fish area and (b) family composition of the households in the rice+fish watershed in LH5 (Fultala).

The community released the fingerlings in the watershed area two weeks after transplanting rice when seedlings had properly anchored with soil. They controlled the outlet of the watersheds for irrigation and drainage and maintained a water depth of 10-50 cm throughout the growing season of rice (August-November). The fish grew well in the canals and flood plain of the watershed mostly with natural feeds (grass and algae grown in the rice field) and with occasional traditional feeding (rice husk). They allowed the fish to grow naturally without artificial feeding.

The community adopted staggered harvesting and selling of fish. Harvesting of fish generally started from December after the rice harvest and continued up to March/April depending on water availability in the canals. After harvest, the community sold a portion (~70%) within the community, consumed and distributed (30%) among the relatives of neighboring villages. In most cases, they also reserved some small fish in the internal canals as stock for the next season.

Although community fish culture in the polders is biophysically simple to implement, there are many challenges to its implementation. The main challenge is community coordination and lack of willingness to implement the fish culture in the rice fields for the benefit of all, including the landless residing around the rice-fish watershed area. Other challenges included profit sharing and yield distribution among the households, social conflict, village, and national political influence, unauthorized harvest and controlling fish escape through rat holes in the village road, tradeoff between high water depth for fish growth vs. low water depth for rat control and yield loss in rice, and short growth period (3-4 months) as fingerlings cannot be stocked before transplanting rice limiting its growth and development.

Despite the above challenges, there are opportunities for integrated rice+fish culture in the 1.2 m ha polder ecosystems of coastal Bangladesh. There are many natural and man-made (by constructing rural roads) watersheds prevailing in the polder ecosystems and lots of small canals and depressions exist in the polders which could be used for community rice+fish culture. Also, integrated rice-fish culture can reduce weed growth (fish ate weeds) and use of herbicides in rice cultivation, conserve natural indigenous fish species as the environment is not disturbed (enhanced breeding opportunities), and is good for nutritional productivity and additional income (although we did not find it economically attractive to the farmers).

The project has introduced zinc-enriched biofortified HYV rice and developed three improved and nutritious cropping patterns suitable for the agro-hydrological environments of the coastal zone.

Objective 3: Introducing Income-Generating Opportunities

The project has introduced mat nursery preparation, transplanting and harvesting paddy by machine and hermetic seed storage for new income generation activities for poor women and landless farmers.

3.1 - Introduced a community seed bank model for income-generating activities for poor women

The farmers in the polder zone usually store their seeds in traditional storages (e.g., gola, motka, plastic drum, a plastic sack, and gunnysack). The project, for the first time, introduced hermetic seed storage facilities placing two cocoons of 1 ton capacity in Fultala (LH5) and Hetalbunia (LH3) villages in polder 30 and provided training to the farmers on the importance of good quality seed production and benefits of keeping seeds in the cocoons. They were provided scientific information on seed production of high yielding, climate-resilient, and nutritious rice, harvest, and post-harvest management. The project introduced this community seed model in which two landless women coordinated the storage process.

Due to high demand among the LH farmers, the cocoon of LH3 was shifted to LH10 (Bayerbhanga village) so that the farmers of four LHs (LH3-LH6) could keep the seeds in the cocoon at LH5 and those from LH7 to LH10 can use the second cocoon at LH10. The farmers used the cocoons to store seeds of both HYV and traditional rice. The farmers used 70−80% traditional rice seeds and 40−66% HYV rice seeds from storage to cultivate on their farms. Seedling mortality due to submergence is a common phenomenon in the coastal zone of Bangladesh. For that, most farmers kept a reserve of 20−40% seeds as buffer stock/security for seedling mortality due to climatic hazards (mostly rainfall-induced submergence). Some farmers also sold about 12% seeds to their relatives and distributed 5−15% of the seeds among their neighbors. The LH farmers mostly had taken care of the storage, engaged two women caretakers for regular inspection of any rat attack for which the farmers paid BDT 2 per kg for the seed to the caretakers. The community reported higher germination of the seeds stored in cocoons (85−95%) vis-à-vis their traditional storage (70−80%).

3.2 - New livelihood options for women and youth in agriculture

The project introduced machines mainly for harvesting paddy to attract women and youth, address labor scarcity in agriculture and also to ease the physical burden on women and increase their contribution to household earnings. Through intensive training, the project team identified three women who showed a strong interest in learning how to use the reapers as a business venture and worked closely with them to develop them as the service providers. Borrowing two reapers from the project, the service providers earned more money (USD 392-503 per year) than they used to do by manual (USD 45-114 per year) harvesting (Figure 8). The young women reckoned that manual harvesting took about 120 hours to harvest one ha of paddy field, while that can be done in only 8 hours with the reaper. It saved their time and reduced drudgery significantly. The additional leisure time had significant implications on women's health and well-being. With the income, the women were able to contribute to their family's welfare such as children's education and marriage, buying and raising poultry and livestock, buying a sewing machine and running tailoring business, and repaying family's long-standing debt/loan.

Although there is a long way to go, mechanization has shown promise in helping increase household income, reducing women's drudgery, and improving their health and overall household well-being. The success of this service provision model using mechanization depends on awareness, training, and access to credit to purchase machines, among other aspects. Although the capital needed to purchase the machines is seen as a major limitation, it can probably be addressed through pooled community investment in conjunction with existing organizational structures such as water management groups or loans from self-help groups/NGOs. Linking these groups to financial institutions might also be an option in the future. The government of Bangladesh has introduced from 50 to 70% of subsidies to acquire agricultural machinery. Linking women to these subsidies will help empower them and move the country closer to ensuring food security and better family health.

Name: Nomita Goldar

Age: 44 years

Education: Grade 7

Household size: 5

Family land holding: 0 ha

Average income with manual harvesting:

BDT 6,000 (22 days of work/year)

Income with mechanical harvesting:

BDT 4,000 (5 days of work/year)

Name: Madhuri Mondal

Age: 37 years

Education: Grade 10

Household size: 4

Family land holding: 0 ha

Average income with manual harvesting:

BDT 3,600 (12 days of work/year)

Income with mechanical harvesting (av of 2 years)

BDT 40,219 (21 days of work/year)

Name: Shipra Biswas

Age: 27 years

Education: Grade 12

Household size: 2

Family land holding: 0 ha

Average income with manual harvesting:

BDT 9,100 (26 days of work/year)

Income with mechanical harvesting (av of 2 years)

BDT 31,344 (14 days of work/year)

Figure 8. Profile of women service provider for mechanical harvesting of paddy in the coastal zone of Bangladesh.

Objective 4: Socioeconomic Assessment Of The Introduced Technologies

4.1 - Analyzed costs and benefits of different cropping patterns, and constraints and opportunities to adopt improved agricultural technologies

A recall survey was conducted by an MS scholar at the early stage (in 2016-17 cropping year) of the project with 180 farm households of six villages in polder 30 to document the productivity, profitability, and trade-off between improved and traditional crops and cropping patterns in the polder zone. The farmers who practiced traditional and HYV rice in *aman* and sesame and sunflower in the *rabi* season were the respondents.

The most dominant cropping pattern was Traditional Rice-Sesame (80%), followed by HYV Rice-Sesame (50%), Traditional Rice-Sunflower (32%) and HYV Rice-Sunflower (22%). The study showed that the yield of HYV rice (4.2 t/ha) was almost double than traditional (2.4 t/h), but sesame as a dry season crop could not increase the system productivity over the newly introduced sunflower. Sesame was badly damaged by rainfall-induced waterlogging, but sunflower a bit resilience to waterlogging (partly damaged, but the yield was reduced). For that sunflower, as dry season crop has increased the system productivity in both traditional and improved production systems. The rice equivalent yield of HYV Rice-Sunflower pattern was 160% higher than the farmers' practice (Traditional Rice-Sesame). The net income of HYV Rice-Sunflower (improved pattern) was almost three times higher than Traditional Rice-Sesame (farmers' pattern). The main reason was that the production cost of sesame (BDT 16,136) was more than the gross income (BDT 5,535), for this reason, the farmers in polder 30 had to abandon its cultivation.

The trade-off among different crops and cropping patterns were analyzed using four domains of Sustainable Intensification (SI) Framework: productivity (yield and yield gap), profitability (net income and income gap), environmental (fertilizer use and pesticide use) and social cohesion. For almost all indicators, HYV rice and sunflower showed superior to traditional rice and sesame and improved vs. traditional cropping patterns, except for yield gap, environment and social cohesion (which is obvious for new crops/cropping patterns). The tradeoff analysis of HYV Rice-Sunflower and Traditional Rice-Sesame is shown in Figure 9). The farmers earned more profit by adopting the HYV Rice-Sunflower cropping pattern than the Traditional Rice-Sesame pattern. However, the high productivity and profitability of HYV Rice-Sunflower came at the cost of large environmental footprints. By optimizing the management practices of the new cropping systems, there are opportunities to reduce the environmental footprints and therefore addressing the food security of the region.

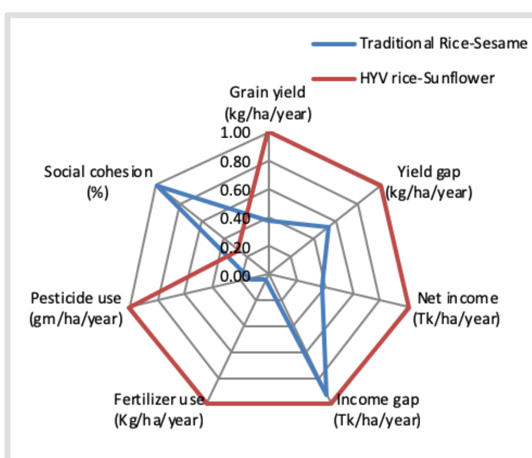


Figure 9. Trade-off between HYV Rice-Sunflower and Traditional Rice-Sesame

Tradeoff analysis of different cropping patterns was also done using direct crop cuts and on the spot survey data collected from 2016 to 2019. As discussed in section 1.4, the farmers of different LHs in polder 30 have adopted three improved cropping patterns with improved water management. Among them, HYV Rice-Maize was the most productive cropping pattern followed by HYV Rice-Sunflower and HYV Rice-HYV Mungbean, productivity was 2-3 times higher than farmers' cropping practice (Traditional Rice-Fallow) under different climatic conditions i.e., in normal, dry and wet years. Like

The new cropping patterns have the potential to address the food security challenges of Bangladesh; still, social cohesion inclines towards traditional cropping practices, as majority farmers cultivate traditional crops in wet and dry seasons due to lack of knowledge and inappropriate water management in the polders of the coastal zone of Bangladesh.

productivity, the net income from the improved cropping patterns was higher than the farmers' pattern but varied depending on the prevailing climatic conditions (Figure 10). In a drought year, HYV Rice-HYV Mungbean (net income $ 759/ha/yr.) was the most profitable cropping pattern, followed by HYV Rice-Sunflower ($539/ha/yr.) and HYV Rice-Maize ($527/ha/yr.), net income was 1-45% higher than farmers' practice. However, in the normal year HYV Rice-Maize (about 3 times farmers' practice) and in wet year HYV Rice-Sunflower (about double than farmers' practice) had more profitability than farmers' practice. Tradeoff analysis showed that HYV Rice-HYV Mungbean was less profitable than farmers' practice in both wet and normal dry years (mungbean damaged due to waterlogging) indicating mungbean is a climate risky crop in the polder environment. But HYV Rice-Maize and HYV Rice-Sunflower patterns showed better climate-resilience, produced at least two times higher yield and income with more fertilizer and pesticides than the traditional farmers' practice.

4.2 - Farmers' perceptions of improved agricultural technologies and practices

A survey with 180 farm households of six villages in polder 30 indicated that most of the respondents showed interest to cultivate HYV rice in *aman* season because of high yield, more profit, early harvesting and ensuring food security. About 97% of farmers stated that HYV rice cultivation is more profitable than traditional rice and high yield is synonymous with food security to more than 92% of the respondent. About 85% of farmers mentioned that HYV rice can be harvested early for which they can cultivate dry season crops timely and can also get the higher market price (HYV rice harvested a month earlier than traditional rice). Another study with 100 farmers of 10 villages in polder 30 indicated that the early availability of HYV rice ensures food security during the lean period. But the farmers (92%) expressed concern on drainage before harvest. Due to the wide-scale cultivation of long-duration traditional rice in polder 30, the drainage from the paddy field is delayed, that delayed harvesting of HYV rice and consequently the farmers' experienced yield loss due to lodging and birds attack. This is the main reason for non-adoption of HYV rice in the polder ecosystem. Additionally, more fertilizer, pesticides and labor requirements (85%); and food habit (63%) were reported for non-adoption of HYV rice in the polder zone.

The main reason for choosing sunflowers as the dry season crop was a high yield (95%) and more profit (98%) than other *rabi* crops. Also, the sunflower is a good/healthy source of edible oil (93%) and can be harvested earlier (88%) than other *rabi* crops. The farmers mentioned that sunflowers might be a climate-resilient crop for the polder environment as the crop can be established and harvested earlier than many *rabi* crops.

But due to the late harvest of traditional rice (92%), high production cost (88%), limited knowledge (82%) and lack of market (74%), they could not widely adopt sunflower in the dry season. The recall survey indicated that the HYV Rice-Sunflower was superior over the traditional farmers' practice in terms of productivity, profitability, nutritional quality and climate-resiliency of the improved cropping pattern. The crop cut analysis showed that the most productive and profitable pattern in a normal year is HYV Rice-Maize and in a wet year, it was HYV Rice-Sunflower. The productivity and profitability of both the improved patterns were almost similar in a dry year. Overall productivity and profitability of improved patterns, HYV Rice-Maize and HYV Rice-Sunflower were three times higher than the farmers' Traditional Rice-Fallow pattern. Therefore, the cultivation of improved cropping patterns is recommended for the food security of the vulnerable polder communities of coastal Bangladesh.

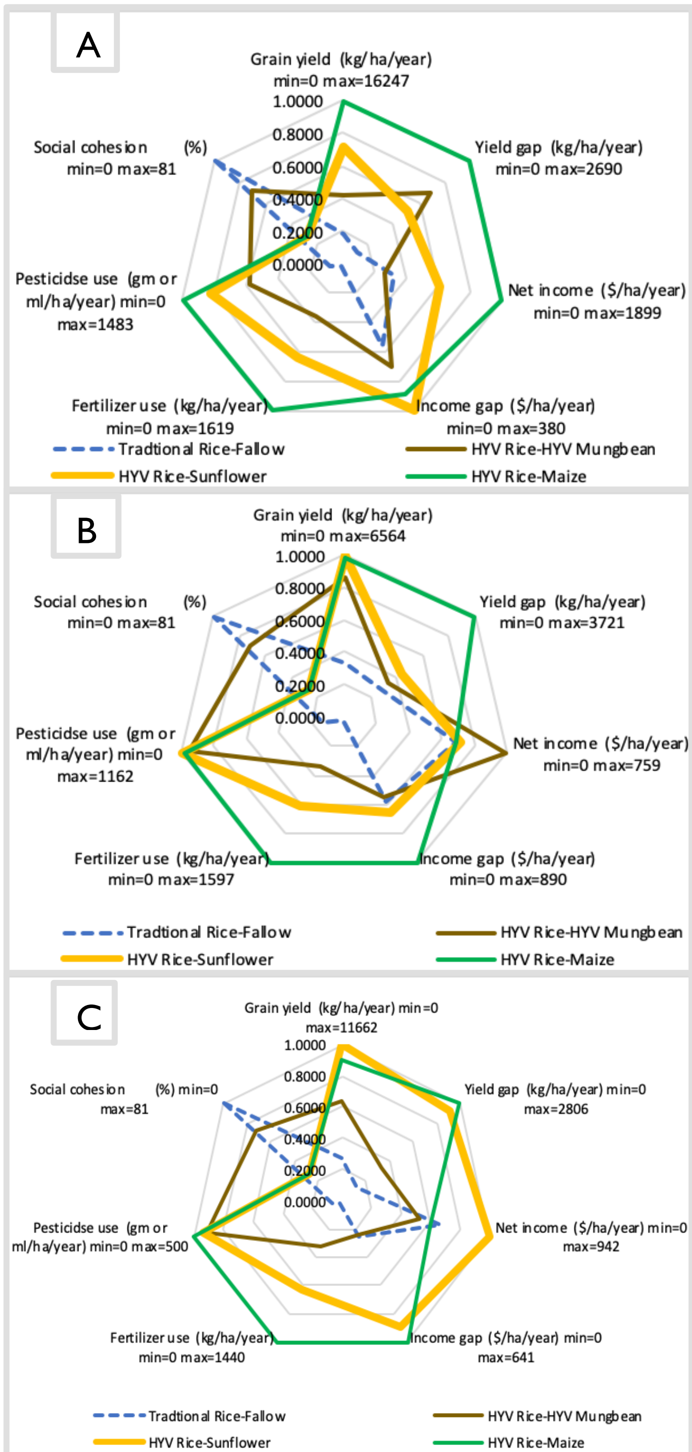


Figure 10. Tradeoff among different cropping system options under different climatic conditions, i.e., in (A) normal, (B) dry and (C) wet years.

4.3 - Perceptions of youth towards joining in agriculture

The study was conducted from randomly selected 270 youth (about 15% women) of ages between 18 and 35 years in polder 30 to document the participation and perception of the youth in agriculture. The study reveals that most of the youth (91%) were less likely to be engaged in farming despite fewer work opportunities in non-farm sectors. Not only the youth, but their parents also discourage them not to accept agriculture as their main profession. But the attitude of the young generation toward farming may change when farming provides a better livelihood and social status. However, the most common perceptions for not adopting agriculture as the main profession are (1) tedious and monotonous lifestyle of a farmer and agriculture demands too much hard work with limited rewards (97%), the youth do not like to work under the sun and in the muddy environment and (2) the young generations (97%) want to join a respectable public or private sector as they consider or even the society see farming is not a respectable profession. But they expressed their concern about future food security and mentioned that the young generation may accept agriculture as the main profession if it is modernized. They mentioned that (1) inclusion agricultural education in academic curricula at the high school level (97%) and onward, (2) removal obstacle of land ownership (97%) for the youth, (3) training on improved agricultural technologies and practices (94%) and (4) development of business-oriented and mechanized agriculture (88%) may attract the youth in agriculture.

Objective 5: Assess The Triple Bottom Line Sustainability Of The Farming System

5.1 - Analyzed economic, social and environmental dimensions of newly developed rice-based production systems under different climatic conditions

The project has developed three improved cropping patterns suitable for different climatic conditions. The patterns are (1) HYV Rice-Maize, (2) HYV Rice-Sunflower and HYV Rice-Mungbean. The productivity of these cropping patterns was much higher than farmers' cropping practice (Traditional Rice-Fallow) under different climatic conditions i.e., in normal, dry and wet years. Likewise, the net income from the improved patterns was higher than farmers' pattern but the gross and net income varied depending on the prevailing climatic conditions. In a drought year, HYV Rice-HYV Mungbean (net income $759/ha/yr.) was the most profitable cropping pattern, net income 45% higher than farmers' practice. However, in a normal year HYV Rice-Maize and in a wet year HYV Rice-Sunflower was more profitable (2-3 times) than farmers' practice. Considering different climatic scenarios, HYV Rice-Maize and HYV Rice-Sunflower showed better resilience and produced at least two-times higher yield and net income than the farmers' practice, but with higher environmental footprints (due to more fertilizer and pesticides use for higher yield). Although the new cropping patterns have the potentials to address the food security challenges of Bangladesh, still social cohesion inclines towards traditional cropping practices, as majority farmers cultivate traditional crops in both wet and dry seasons.

5.2 - Analyzed the benefits of pump drainage for wet season rice cultivation to address future climate change scenario

The cropping intensity and productivity in the polders of the coastal zone are low due to the adoption of traditional agriculture. The general perception is that salinity is the main reason for the non-adoption of improved agricultural technologies in the coastal zone of Bangladesh. In reality, the root cause of low cropping intensity and productivity is poor water management; in particular, the lack of drainage during and at the end of the wet season that hinders the adoption of HYV rice and delays the harvest of traditional rice. The late rice harvest and waterlogged soil prevent the timely cultivation of dry season crops. But there are tremendous opportunities to capitalize on polder ecosystem services especially the tidal river dynamics, dense canal networks, and water management infrastructure to reduce waterlogging by gravity drainage during low tides and greatly increase land productivity.

There is a prediction that sea-level rise is expected to shift the coastal periphery inland and could reduce the land area by 17% (due to a waterlogged environment). Many people are advocating pumping out water as an option for maintaining the livelihood of the community residing in the polders of the coastal zone of Bangladesh. Therefore, a study on the effectiveness/benefits of pump drainage was conducted involving an MS student (a senior engineer of BWDB, the organization responsible for water resources development including polder management) in 2018. Although the crop was not submerged, pump drainage was required to topdress nitrogen fertilizer at the panicle initiation stage and for terminal drainage to facilitate harvesting of HYV rice. Therefore, it is inevitable that HYV rice cannot be widely adopted in the polder zone (land elevation within 1-2 m above mean sea level) unless a favorable water environment is created either by gravity drainage or by pumping. Different scenario analysis revealed that energy-fed drainage is profitable for rice cultivation in the polder environment. Adoption of HYV rice instead of low-yielding traditional rice will further increase the net return from *aman* rice cultivation. Sensitivity analysis indicated that future rice production will be profitable even if the lands in the polders are waterlogged (as predicted by IPCC 2013) and need pump drainage to create a favorable environment for rice cultivation in the wet season.

Objective 6: Enhance Institutional, Extension And Research Capacity Building

The project introduced the concept of a signal platform to engage with different stakeholders and their capacity building. By introducing a four-dimensional learning hub approach the project achieved active collaboration between researchers, extension personnel and practitioners (see Polder Tidings Vol 2 (2): 6-7).

The project has developed knowledge and communication material on (1) water management and governance, (2) production practices of climate-resilient and nutritious rice, (3) production practices of sunflower, maize, and mungbean, (4) mat nursery preparation, (5) use of transplanter for transplanting rice, (6) use of reaper for harvesting rice, and (7) on human nutrition using zinc-enriched rice and nutritious *rabi* crops. The project team has been quite active in sharing the learning through peer-reviewed journal articles, presenting learnings in international and national workshops and meetings

6.1 - Awareness and capacity building on human nutrition

Since more than 70% population in the polders relies on a cereal-based diet with a very small proportion of protein and micronutrients, undernutrition is a serious challenge in Bangladesh. In the polders of the coastal zone, the situation exacerbates further with a significant part of the population not having sufficient food supply throughout the year. More than just food access, nutritional security depends on awareness about the need for nutrition-rich farming systems and dietary diversity. The project introduced biofortified zinc rice, sunflower, and maize for improving food and nutrition among the polder communities. Many studies indicate that increasing mothers' knowledge of nutrition may contribute significantly to the nutritional status of the family, especially the children.

To create a knowledge hub on nutrition, 57 training events were organized at 18 sites involving the male and female teachers of the primary and high schools, mothers of kindergarten, primary and high school children and household members of the LH farmers in polder 30. The main reason for involving the school teachers is to empower them about the nutritional aspects of zinc bio-fortified rice, sunflower oil, nutrition from pulses and maize that the project has introduced in polder 30 so that they can teach their students on those nutritious crops. The importance of micronutrients and protein on the overall nutrition of children, pregnant and lactating mothers were shared with 970 participants, of which 84% were women.

It was observed that the farm families have started utilizing sunflowers as edible oil, and using leaves and grains of maize for feeding livestock, poultry and fish via which the household's intake of egg, fish, meat, and milk increased.

6.2 - Enhanced knowledge and skills of the young agricultural scientists

Capacity building at all levels was a key component of the project, including training farming communities, representatives of water management organization and union parishad, extension workers, and future agricultural scientists in the region. An integrated research platform was developed wherein fourteen postgraduate students from different disciplines of local universities were engaged in identifying opportunities, and devising solutions for water resources management, cropping intensification and diversification towards improving human nutrition and farm income in the polders. The project developed partnerships with four universities in Bangladesh (Bangladesh Agricultural University, Sher-e-Bangla Agricultural University, Patuakhali Science and Technology University and Khulna University), through the provision of scholarships for postgraduate students to work in the project, with particular emphasis on coastal zone agricultural production systems and water management. Out of 14, one student enrolled at the University of Arkansas in the USA. The students conducted studies on different aspects of production systems and their tradeoff, water governance, market study, gender, income, and nutrition. Of the 14 scholars, nine completed MS and three completed their Ph.D. from 2017 to June 2019. The remaining two Ph.D. students have completed data analysis and the first draft of the thesis is on-going. They are expected to complete their Ph.D. by the end of 2019.

Figure 11. Targeted area of research for capacity building of MS and Ph.D. students

Three Ph. D. graduates have started their professional career – two at BRAC and one at the University of Arkansas, USA. The rest two Ph. D. candidates have also got a job in the private sector. Among the MS graduates, two have got a job in the private sector and one government official has returned to his organization, Bangladesh Water Development Board, after completing his MS degree. The remaining MS graduates are looking for a government job, and some of them are engaged in part-time assignments in the private sector/NGOs.

6.3 - Enhanced knowledge and skills of farmers and extension personnel on improved resource management and production systems

Management of tidal river water through sluice gate operation is the key to wide-scale and year-round adoption of improved agricultural technologies in the polders of the coastal zone of Bangladesh. However, only knowledge of the production system will not help the farming community to intensify and diversify cropping in the polder ecosystem. Therefore, the project provided training (Figure 12) on integrated water management and synchronized cropping in both wet and dry seasons to 1807 farmers, members of WMOs and public representatives of union parishad (UP), and local leaders, of which 38% were women (mostly spouses of the farmers, members of WMOs and UP). The highlights of the training events were the importance of sluice gate operation to maintain a favorable water environment for HYV rice cultivation in *aman* season, importance and timing of drainage especially during the critical growth stages of rice, importance and timing of terminal drainage for soil drying for rice harvest and consequently the early establishment of *rabi* crops for higher yield and safe harvest. Thus, the project enhanced the knowledge and skills of the farmers, WMOs and UP representatives in polder 30.

> The WMOs adopted improved water management in *aman* season and adopted terminal drainage about two weeks earlier than a traditional practice. This water management not only encouraged the mechanical harvesting of rice but also enhanced the early establishment of *rabi* crops in the dry season.

The project also organized short-term training on different aspects of integrated crop and water management including agricultural mechanization, and nutritional awareness among the polder communities (Figure 12). Hands-on training on (1) climate-resilient and nutritious rice varieties and production procedure, (2) polder water management and sluice gate operation for water management organizations and representatives of union parishad, (3) mat nursery preparation, (4) mechanical transplanting of rice, (5) rice seed production, (6) pest management including rodent management in HYV rice, (7) safe pesticide application by battery-operated sprayer, (8) mechanical harvesting rice, (9) residual soil water management and cultivation of *rabi* crops, (10) use of power tiller operated seeder (PTOS) for sowing seeds of *rabi* crops, (11) hermetic storage - community seed bank model, (12) nutritional awareness among mothers, school teachers, and farmers, and (13) troubleshooting of agricultural machinery for about 6000 participants, among them 48% were women. Thus, the knowledge and skills of the farming community and community leaders were improved which was transplanted in their farming and in-polder water management.

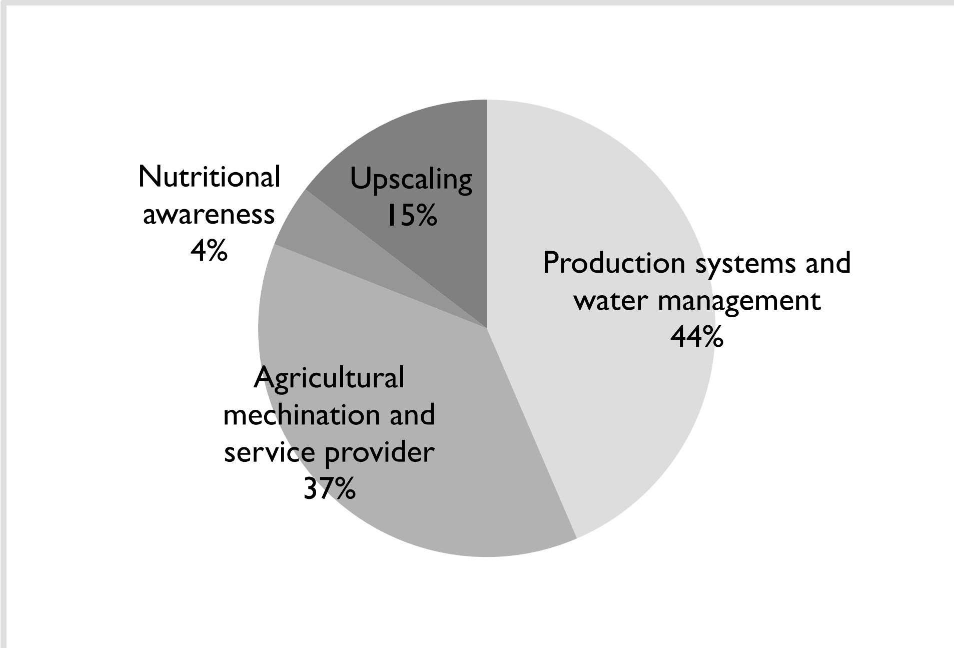


Figure 12. Skills targeted for the capacity building

Objective 7: Upscale And Outscale Successful Farming Technologies

7.1 - Organized traveling seminars and field days for farmers, local leaders, and extension workers

The project team has organized 20 traveling seminars/field days in nine LHs in *aman* and *rabi* seasons to demonstrate the performance of climate-resilient and nutritious rice, use of machinery to transplant and harvest rice, the performance of maize, sunflower and mungbean and importance of the new cropping patterns for food security, income and household nutrition. The project adopted the husband-wife model (improving whole family knowledge) to upgrade knowledge of 946 participants including 516 women (and their spouses) from the farming community, officials of DAE, members of the WMOs, public representatives of the local government institutions (Union Parishad-UP) and local elites. The participants recognized the importance of in-polder water management for sustainable agriculture to address the food and nutritional security challenges of the polder communities of Bangladesh.

7.2 - Developed knowledge-sharing platform for upscaling project findings

The project has established a Knowledge Sharing Platform (KSP) and organized three workshops (Figure 13) under the leadership of the Bangladesh Agricultural Research Council (BARC) for improved sharing, networking, complementarities and synergies across the many R4D projects on production systems (agriculture, aquaculture) and water management in the Ganges coastal zone, with the ultimate goals of improved livelihoods, productivity, resilience, and sustainability. The first workshop was organized in Bangkok and the last two in Dhaka in which prominent agricultural scientists, water management specialists, and agricultural extension professionals, policymakers, and journalists from the National Agricultural Research and Extension Systems (NARES), international research organizations, national and international universities, development partners, NGOs, and mass media participated. The participants (161 participants from 22-28 organizations) have shown a keen interest in sharing knowledge for the development of the coastal zone and are expected to strengthen the KSP under the leadership of the Bangladesh Agricultural Research Council (BARC) with technical backstopping from IRRI.

Figure 13. Knowledge sharing platform meetings organized yearly under the leadership of Bangladesh Agricultural Research Council, the apex body of the National Agricultural Research System and co-convene by IRRI with support from RICE CRP and SIIL.

7.3 - Shared knowledge on integrated crop and water management to stakeholders

As part of project strategies for upscaling and scaling of interventions, the project team is actively engaging with other stakeholders and organizations to share learning from the polder environment. The project team participated in the national and international seminars and presented papers related to productivity improvements in the polders of the coastal zone and/or shared project outputs to different stakeholders including scientists, academicians, extension professionals, policymakers and mass media. Besides, a team member had a courtesy meeting with the Honorable Minister for Agriculture, Government of Bangladesh, Dr. Md. Abdur Razzaque on 31 January 2019 where the issues on cropping intensification in the coastal zone for food and nutritional security of Bangladesh were shared.

7. Utilization of Research Outputs

One of the key outputs of the project is the development of improved, resilient and profitable cropping patterns through community-led water management suitable for agro-hydrological environments prevailing in the polders of the coastal zone of Bangladesh. The outputs are being adopted both at the community and organization level for upscaling at a limited scale in different polders of the coastal zone of Bangladesh.

Community-Level

The WMOs in polder 30 have started adopting in-polder water management through sluice gate operation that created a favorable water environment for HYV rice adoption and fertilizer management in the polder ecosystem. Consequently, the neighboring farmers of the LHs in polder 30 have started adopting improved cropping patterns developed during the project period for food and nutritional security.

Organizational Level

The Blue Gold Program of the Royal Dutch Government in partnership with Bangladesh Water Development Board (BWDB) and Department of Agricultural Extension (DAE) has been promoting the learning of cropping intensification through improved water management involving the community since the *aman* season 2016. They are implementing CAWM (community agricultural water management) schemes in 22 polders to reduce poverty and stimulate economic development in coastal polders through improved water resource management and enhance agricultural productivity and profitability. Owing to field-level experience, the DAE is planning to mainstream the integrated polder water management and synchronized cropping in the coastal zone of Bangladesh.

Livelihood Impact

The project introduced the agribusiness model received traction both at the community and organization level. After the initial learning phase, the women service providers are extending their business by reaching to far-distance farmers also for the harvesting of their paddy. Similarly, the results of the feasibility of dry season crops especially sunflower has attracted the interest of traders/millers to initiate contract farming in the polder region.

8. Future Challenges and Opportunities

Both challenges and opportunities are built-in in the coastal ecosystem; it has huge resources and also receives hazards to destroy the assets and livelihood of the communities developed utilizing those resources. This ecosystem comprises low-lying lands with a dense network of rivers and canals and is strongly affected by cyclones, tidal surge and salinity intrusion. The rivers are tidal, and this effect extends up to about 150 km inland.

The huge water resources in the coastal zone are vital for agriculture, ecosystem sustenance, and livelihood. About 1.2 Mha lands are enclosed within 139 coastal polders; each having several sluice gates/regulators and canal networks to create favorable water environment for round the year cropping. But both the resources in the polders are underutilized, offer huge potential for Bangladesh to make a quantum leap in meeting future food security requirements and achieving SDG 1 (no poverty) and SDG 2 (zero hunger).

While tens of millions of dollars are invested in developing and maintenance of the polders, the coastal zone is still home to the poor, food-insecure and most vulnerable rural people. There have been tremendous improvements in cropping system technologies over the past 50 years. Bangladesh has achieved self-sufficiency in rice using those technologies. But the coastal zone is deprived of this technological advancement. Since the hydrology of the coastal zone is quite different from other parts of the country, it is practically impossible for an individual farmer in the polders to manage huge tidal river water for improved cropping, while an individual in non-coastal zone manages groundwater for his/her food security without much difficulty. Using the FFS model, the DAE has successfully disseminated improved agricultural technologies in the non-coastal zone. But there has been little change in production practices in 1.2 M ha lands in the polders since its construction 50-60 years back, as the hydrology was not considered as a determinant in technology dissemination in the coastal zone of Bangladesh. Still, this has not been recognized by the policymakers, water management and extension professionals, and the millions of farming families living inside the polders. A whole-polder water management study should, therefore, be conducted to convince the policymakers, water management, and agricultural extension professionals to adopt synchronized crop and water management in the polder ecosystem to future food security of Bangladesh.

The key challenges and opportunities for wide-scale adoption of the improved agricultural technologies are highlighted below:

Challenges For Cropping Intensification In The Coastal Polders

- **Water management and crop intensification**
  - Organizing community-based on the hydrological area (e.g., catchment area of a sluice gate/regulator), not by geographical area (e.g., by village), which is currently practiced; without which wide-scale adoption of improved agricultural technologies will not be possible in the polders of the coastal zone of Bangladesh.

    - Wide-scale adoption of HYV rice (replacing long-duration traditional rice) in the wet season is the key for cropping intensification in the polders of the coastal zone of Bangladesh, which is restricted by the prevailing hydrology and poor water management. Fertilizer management at the key growth stages of rice is hindered by high water depth and consequently low yield and profit of the farmers. The adoption of a catchment-level or whole-polder water management approach may solve this problem. Also, the declining market price of paddy in recent years is discouraging farmers to adopt HYV rice.

- **Crop establishment and management in the dry season**
    - Delayed soil drying restricted the timely establishment of *rabi* crops, and how to establish the crops on moist soil and effectively utilize residual soil for *rabi* crops cultivation pose a big challenge for the community.
    - Fertilizer management in *rabi* crops when established by zero or minimum tillage, especially topdressing of nitrogen at later growth stages of the crops. The topsoil becomes dry/hard, and freshwater is not available for irrigation. The introduction of mini-tractor (~50 cm width) to plow in between two crop rows may solve the problems of soil cracking and fertilizer management in the dry season.

- **Agricultural mechanization**
    - Excess water in the wet season poses the use of rice transplanter and muddy soil even after crop maturity restricts the use of reaper for harvesting paddy.
    - Lack of appropriate machines for sowing seeds on moist soil, and plow in between crop rows for fertilizer and weed management for *rabi* crops.
    - The Department of agricultural extension (DAE) lacks appropriate human resources to promote mechanization and mentor the farming community.
    - Poor road network and intensive canal systems in the polders are the main hindrances to move agricultural machinery from one place to another.
    - Non-availability of experienced operator and mechanic in the locality.

- **Rice+fish integration**
    - The rice+fish community system is good for nutritional productivity and additional income; however, we did not find it economically attractive to the farmers. There could be many reasons including leakages, unauthorized harvest, fish species compatibility, social cohesion, and the tradeoff of maintaining water depth for controlling pest/rodents vs growth of fish (low water depth and short growing period in the wet season hindered the normal growth of fish species).

Opportunities For Cropping Intensification In The Coastal Polders

1. Underutilized land and water resources

The coastal zone of Bangladesh is blessed with huge water resources. In the rivers, high and low tides occur twice daily. Water level elevation at high tides remain higher and at low tides is lower than the land elevation, offering opportunities for gravity irrigation and drainage. The project has developed appropriate water management and agricultural technologies for year-round cropping in the polders. The key prerequisite to its adoption is the irrigation and drainage management during *aman* season mainly to topdress nitrogen fertilizer at critical growth stages of rice and in early November before rice harvest (for timely harvest) and timely/early establishment for a safe harvest of *rabi* crops. These technologies can be upscaled to the entire polder zone through intensive training of the WMOs at the polder scale and demonstration of water management and coordinated efforts of improved cropping practices at a catchment level (catchment area of a sluice gate/regulator). Thus, Bangladesh can make a quantum leap in meeting future food security requirements utilizing the free tidal river water resources for agricultural intensification in the polders of the coastal zone of Bangladesh for food and nutritional security of the communities and in achieving SDGs 1 and 2.

2. Exploring and testing the dry season crops to improve farm productivity and human nutrition

The traditional dry season crops that some farmers used to cultivate are often damaged by pre-monsoon at or near harvest and incur a huge loss. For this reason, most of the lands remain fallow in the dry season. The project has shown that maize and sunflower have significantly increased productivity and profitability in the dry season under various climatic environments. Large-scale demonstration of the resilient dry season crops (maize and sunflower) with appropriate agronomic management in different polders may lead to wider adoption in the polder zone. Consumption of maize grain and sunflower oil is expected to improve household nutrition further. Also, the production and consumption of sunflower oil at the household level is expected to develop the market within the locality. The maize grain and leaves may be a source of alternative feed for the livestock (serious fodder scarcity in the dry season). Wider demonstration of maize and sunflower is expected to attract the buyers; thus the farming community could get higher benefits through improved market linkages.

3. Supporting service economy through agri-entrepreneurship

Almost all the agricultural operations in the coastal zone are done manually, except land preparation. There is a large scope for the development of agri-entrepreneur for livelihood improvement of the poor women and landless youth at the same time sustaining agricultural growth in the polders of the coastal zone of Bangladesh. The project has shown the pathway of women engagement in agriculture for improving their livelihood with more income by being a service provider in mechanical harvesting of paddy instead of doing it manually, which also reduced their drudgery to a great extent. Also, the community seed bank model offered another opportunity for the improved livelihood of poor women. Development and mentoring of the service providers in harvesting paddy, intercultural operation of dry season crops, and hermetic seed storage is expected to render new livelihood opportunities for the poor women and may attract the landless youth to become service providers that might help in sustaining future agricultural growth living in the polder zone. Similarly, the introduction of new dry season crops will create the opportunities to use power-tiller operation and that will further bring entrepreneurship prospects for youth and women. The government of Bangladesh has declared up to 70% subsidy on purchasing machines for agricultural mechanization in the coastal zone, linking the service providers with these opportunities is expected to further accelerate the agricultural growth in the coastal zone of Bangladesh.

Transplanter operation in Noakhali, Bangladesh. Photo credit: Md. Humayun Kabir.

9. Publications

The project has been proactive to share learning through research articles, strategic communication material, presenting the work at the international forum. The publications generated through SIIL funding are listed below:

1. Bhattacharya et al. (2019) The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh. Field Crop Research Vol 234, 33- 46. https://doi.org/10.1016/j.fcr.2019.01.007
2. Shew et al. (2019) Rice intensification in Bangladesh improves economic and environmental welfare. Vol 95, 45-57. https://doi.org/10.1016/j.envsci.2019.02.004
3. Shew et al. (2019) Identifying dry-season rice-planting patterns in Bangladesh using the Landsat archive. Vol 11, https://doi.org/10.3390/rs11101235
4. Yadav et al. (2019) Making inroads to intensify agricultural productivity in the polders of the coastal zone of Bangladesh. Paddy and Water Environment (under review)

Strategic Communication/Blogs

1. Mondal, M., Sudhir-Yadav, 2018. The food-water-energy nexus: Using gravity drainage to intensify production systems in the coastal zone of Bangladesh. Rice Today. International Rice Research Institute, Los Baños, Philippines, pp. 28-29.

Newsletters

The project has shared the learnings through the biannual newsletter "Polder-Tidings". A total of 35 articles were published through this newsletter.

Sharing Results At An International And National Forum

The project team presented four papers in the international conference based on the research results of the project. The paper on (i) Concept of hydrology-based agricultural technology dissemination for wider adoption of improved agricultural technologies in the polders of the coastal zone of Bangladesh was presented in the International Conference on Research and Extension for Sustainable Rural Development organized by the Bangladesh Agricultural Extension Society on 15 to 16 February 2018; (ii) An innovative water management approach for increasing land productivity in the polders of the coastal zone of Bangladesh was presented in the plenary session on natural resources management in the International Conference on Climate Knowledge on 8-11 January 2019; (iii) Land productivity improvement opportunities in the coastal polders to address food security challenges of Bangladesh was presented in the Third International Conference on Sustainable Development held on 19-20 February 2019; and (iv) Using multi-temporal remote sensing data to analyze the Spatio-temporal patterns of dry season rice production in Bangladesh was presented in the conference organized by the International Society for Photogrammetry and Remote Sensing. Also, two papers were accepted for oral presentation in the Second and Third World Irrigation Forum: (i) An innovative water management approach for food security of coastal zone communities in Bangladesh and (ii) Is gravity drainage viable option for cropping intensification in polders of the coastal zone of Bangladesh? The learnings of the project on integrated water management and synchronized cropping for improving the productivity of the coastal zone were presented in at least 10 national workshops, seminars and meetings organized during the project period.

10. Datasets Produced

The project team has collected data on the productivity and profitability of rice, maize, sunflower, mungbean and rice-based cropping patterns, mechanized rice cultivation, and capacity building of the community and new generation scientists and professionals.

Dataset	Repository	Notes
SIIL-Polder Baseline survey	SIIL Dataverse	Baseline survey in the polders of coastal Bangladesh.
Crop performance data- Sustainable intensification options in polders 30, Bangladesh	SIIL Dataverse	As part of the SIIL-Polder project, adaptive experiments were conducted on crop intensification and diversification. The data of grain yield was collected using a crop-cut method.
Raw data PhD thesis: The feasibility of high yielding aus-aman-rabi cropping systems in the polders of the low salinity coastal zone of Bangladesh	SIIL Dataverse	This data set is the raw data from the PhD thesis evaluating the feasibility of high yielding ausaman-rabi cropping systems in the polders of the low salinity coastal zones of Bangladesh.
Raw data of PhD research: The feasibility of high yielding triple rice systems in the polders of the low salinity coastal zone of Bangladesh	SIIL Dataverse	This data set is the raw data of PhD research evaluating the feasibility of high yielding triple rice systems in the polders of the low salinity coastal zone of Bangladesh.
Raw Data for MS thesis on: Fertilizer management of HYV rice in the polder ecosystem of the coastal zone of Bangladesh	SIIL Dataverse	This data set is the raw data from the MS thesis on fertilizer management of HYV rice in the polder ecosystem of the coastal zone of Bangladesh.
Raw Data for MS thesis on Fertilizer management of HYV rice in the polder ecosystem of the coastal zone of Bangladesh	IRRI Dataverse	The raw data from the MS thesis on fertilizer management of HYV rice in the polder ecosystem of the coastal zone of Bangladesh.
Raw data MS research "Market Response to Improved Rice Varieties in the Coastal Bangladesh: A Case Study on Polder 30in Batiaghata Upazila in Khulna District"	IRRI Dataverse	The raw data from MS research on "Market Response to Improved Rice Varieties in the Coastal Bangladesh."
Raw data for MS thesis research "Effect of transplanting date on the growth and yield of aman rice in polder ecosystem of the south-western coastal zone of Bangladesh"	IRRI Dataverse	The raw data for MS thesis research on "Effect of Transplaning Date on the Growth and Yield of Aman Rice in Polder Ecosystem of the South-Western Coastal Zone of Bangladesh."
Raw data: MS research on "Perception and participation of youth in agriculture: a case in polder 30 of southwest coastal zone of Bangladesh"	IRRI Dataverse	The raw data from MS research on "Perception and Participation of Youth in Agriculture: A Case in Polder 30 of Southwest Coastal Zone of Bangladesh."

CAMBODIA

Cambodia

Women in Agriculture Network (WAgN)-Cambodia: Gender and Ecologically-Sensitive Agriculture

1. Lead Institution: Pennsylvania State University (PSU)

- U.S. Collaborating Institutions:
  - University of Tennessee Institute of Agriculture (UTIA)

- International Collaborating Institutions:
  - Agricultural Development Denmark Asia (ADDA)
  - World Vegetable Center (AVRDC)
  - Asia Impact Center – ECHO
  - Kasetsart University
  - Royal University of Agriculture (RUA)
  - Conservation Agriculture Service Center (CASC)
  - University of Battambang

2. Research Team

- Lead Investigator:
  - Ricky Bates (PSU)

- Co-Investigators:
  - David Ader (UTIA)
  - Uon Bonnarith (ARVDC)
  - Poonpipope Kasemsap, Kasetsart University
  - Ann Tickamyer (PSU)

3. Executive Summary

PSU and partners implemented the WAgN-Cambodia project to empower women and improve nutrition by promoting women's participation in the value chains for horticultural crops produced through sustainable intensification (SI) practices. The overarching goal of the project was to provide a scientifically rigorous and comprehensive understanding of the nexus of gender and SI. This enabled us to develop, inform and deploy synergistic programs to enhance women's status and advance SI. We aspired to improve the socio-economic and nutritional status of women and their families as well as identify, develop and strengthen existing and potential SI technologies, practices and policies that promote the production of nutritious and marketable food, while protecting agro-ecological resources. The project pursued four major objectives: first, to identify and promote adoption of gender-sensitive SI technologies and practices in horticulture value chains, targeted to improve ecological resilience as well as the nutritional status and income for poor households; second, to identify and foster enabling conditions and social networks for women to fully participate in the local, regional and international value chains for horticultural-based foods produced via SI; third, to build capacity in local agricultural institutions, NGOs, and international universities and research institutes, to scale up and out innovations in gender and ecologically sensitive SI; and finally, to test the SI assessment

> Project results emphasize that horticultural and other foods produced by smallholder farmers via SI are produced and distributed through value chains that can be exploited to create new opportunities for women and improve the nutrition of their families.

framework in alignment with project objectives and activities. The project promoted gender equity and family nutrition by understanding and addressing barriers to women's participation in horticulture value chains and adoption and the use of SI technologies and practices. Our project stressed the importance of markets and promoted efforts to move Cambodian agriculture towards a market-driven system.

4. Project Partners

The WAgN project relied on several key implementers and cooperating organizations to accomplish its stated goals and objectives. These included:

- The University of Tennessee - Knoxville, Tennessee, U.S.A.
- University of Battambang - Battambang, Cambodia
- Royal University of Agriculture - Phnom Penh, Cambodia
- Kasetsart University - Bangkok, Thailand
- Agriculture Development Denmark Asia (ADDA) – Siem Reap, Cambodia
- The World Vegetable Center - Siem Reap, Cambodia
- CIRAD - Bos Khnor, Cambodia

5. Project Goals, Objectives and Activities

Overall Goal

The overall goal of the WAgN project was to develop the capacity for Cambodia to be the "Center of Sustainable Intensification" in Southeast Asia.

Overall Objectives And Activities

The overall objectives included to identify, develop and strengthen existing and potential SI technologies, practices and policies in Cambodia through both gender and ecologically-sensitive approaches.

Objective 1: Identify and promote adoption of SI technologies and practices in rice and horticulture value chains, targeted to improve farm system resilience as well as the nutritional status and income for poor households.

WAgN's first objective aimed at facilitating solutions to food security constraints at the grassroots level and embedding innovations into social networks. Activities engaged relevant stakeholders such as farmers, service providers, agronomists, scientists and traders, in the innovation discovery process in designing appropriate SI practices and technologies in the local context. Key information was collected from our household survey, previous and ongoing research, and robust stakeholder engagement. To accomplish this, project activities included:

- Identifying a suite of existing and potential SI technologies and practices for horticulture production in limited-resource settings.

- Field-testing SI technologies and practices for horticulture production.

- Co-design with relevant stakeholders, using gender-inclusive approaches, diversified lowland farming systems that are ecologically-sensitive and based on SI principles.

- Introducing SI technologies and provided gender-sensitive SI and nutrition training.

Objective 2: Identify and foster enabling conditions and social networks for women to fully participate in the local, regional and international value chains for horticultural and rice-based foods produced by SI.

WAgN's second objective focused on the identification of enabling conditions and social networks to support and enhance SI. To accomplish this, project activities included:

- Identify policies and cultural norms that limit the participation of women and other marginalized populations in the horticulture and rice value chains for SI.
- Identify barriers to and opportunities for women's participation in farmer groups and securing leadership and decision-making roles in organizations.
- Identify barriers to and opportunities for women's adoption of SI technologies and practices (cultural, technical, financial, time use, labor, etc.).
- Provide gender-sensitive leadership training in local and national organizations.
- Provide training to women's groups and other marginalized producers in negotiation, marketing, and access to credit and markets.

Objective 3: Build capacity in local agricultural institutions, NGOs, and international universities and research institutes, to scale up and out innovations in gender and ecological-sensitive SI.

WAgN's third objective aimed to strategically build the capacity of a) smallholders, service providers, researchers, development extension staff, and cooperating universities in managing complex innovation discovery networks, and b) professors/lecturers and a new generation of plant scientists and researchers in designing and assessing SI systems and technologies. Grassroots knowledge contributed to creating synergies with development operators, NGOs, and development agencies. To accomplish this, project activities included:

- Support research programming (Ph.D. and MSc training) for partner universities (Royal University of Agriculture; University of Battambang) in partnership with Kasetsart University and SEARCA.
- Create curricula and provide training for regional NGOs, governmental agencies, and educational institutions working in agriculture and community development.
- Enhance the flow of knowledge between relevant stakeholders and development operators, NGOs, governmental agencies, the scientific community and policy-makers.
- Develop a scalable model and tools to increase the adoption of SI technologies, practices and policies across the Southeast Asia region.

Objective 4: Test the SI assessment framework in alignment with project objectives and/or activities.

WAgN's fourth objective utilized the SI Assessment Framework developed by the SIIL at Kansas State University to improve project monitoring and evaluation. This framework presents a system to measure objective-oriented indicators under five critical domains: productivity, economic, environmental,human condition, and social, with consideration across three scales: landscape, farm/household, and field/herd. To accomplish this, project activities included:

- Select initial SI assessment framework indicators representing each domain.

- Develop the corresponding poster to reflect integration of the SI assessment framework domains within the project.
- Participate in SI assessment framework training at the 2017 SIIL Annual Meeting.
- Team participation in individualized SI assessment framework in-country training.

6. Accomplishments

A challenge to diversifying smallholder systems is to identify useful technologies to address the temporal-spatial-functional components of SI. Food security remains a challenge for many smallholder farm families. Demographics and food security data were collected in a random sample of households (n=394) in three provinces in Northwest Cambodia at the beginning of the project. Descriptive and inferential statistics were conducted to analyze the relationships between identified determinants of household food security and SI processes. Our findings indicate that households that are more food secure have access to larger land areas (see chart 1). Recognizing that expanding land acreage under production is not a viable option for the majority of Cambodian smallholders, we also examined household characteristics, socio-economic conditions and agricultural SI practices for evidence as they determine food security. The WAgN project focused on finding solutions for smallholders to increase income and food nutrition. There were multiple accomplishments made during the life of the WAgN project. They are presented below according to each objective.

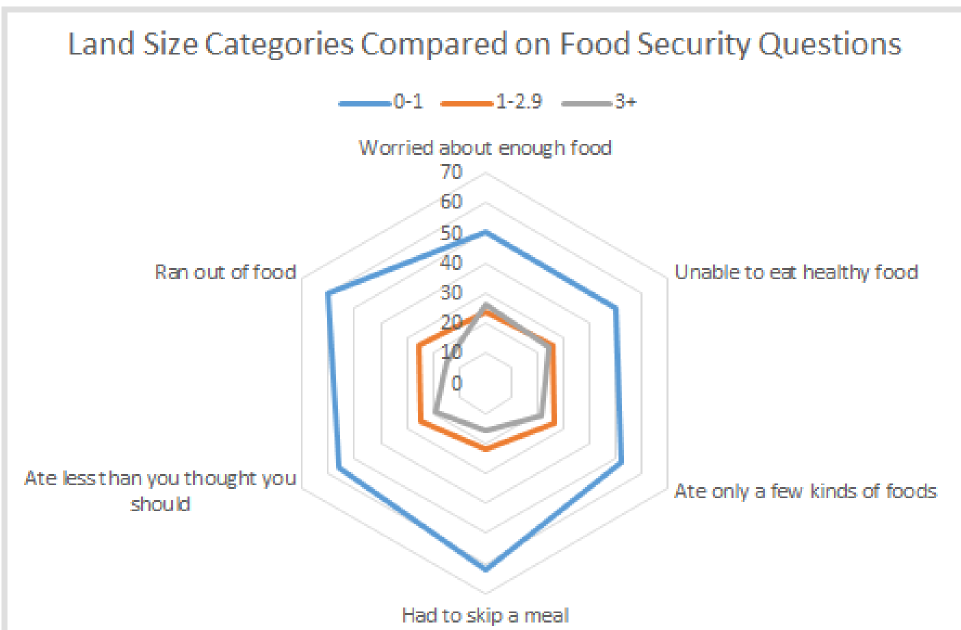


Chart 1: Through descriptive and inferential statistics, the WAgN project found households that are more food secure have access to larger land areas, which is not a viable option for the majority of Cambodian smallholders.

Objective 1: Identify and Promote Adoption of SI Technologies and Practices in Rice and Horticulture Value Chains, Targeted to Improve Farm System Resilience as well as the Nutritional Status and Income for Poor Households

Tomato Grafting

'Makis' tomato variety grafted onto Eg 190 eggplant rootstock, Battambang province, Cambodia. Photo credit: Ngang Channaty.

Rainy season tomato production in Cambodia between July - October is affected with problems due to flooding, waterlogged soils, root-knot nematodes and soil-borne diseases. The overwhelming majority of vegetables consumed in Cambodia during this period are imported from other countries and are expensive. Grafting tomato scions onto local landraces of eggplant rootstocks, as well as a suite of eggplant rootstocks obtained from the World Vegetable Center, solved this problem and made it possible to produce market-demanded tomatoes during the rainy season.

These eggplant rootstocks, and eggplant landraces collected from farms in Battambang and Siem Reap provinces, were extensively evaluated to measure resistance to the key soil-borne pests present in Cambodia, as well as rootstock tolerance to nematodes and waterlogged soil conditions. Additionally, scion-rootstock compatibility of popular market-demanded tomato varieties was determined. Top-performing tomato-eggplant rootstock combinations were identified to establish recommendations for producers. Best management practices were identified and presented during training events.

A team of key project collaborators were trained and achieved proficiency in vegetable grafting techniques. This team worked with farmers, NGO staff, university staff, and students across Cambodia to train stakeholders in basic grafting techniques, and to lay a broad foundation for future vegetable grafting scale up.

The WAgN project engaged key Ministry of Agriculture, Forestry and Fisheries (MAFF) and Ministry of Education Youth and Sports (MOEYS) representatives to promote and facilitate vegetable grafting as an important SI technology for future scale up.

The WAgN project also acknowledged CE SAIN as an important outreach, research and training platform. Tomato grafting demonstrations were established at several CE SAIN technology parks. The SIIL/USAID WAgN-Cambodia project was highlighted on national news by the Hang Meas News Agency. The story highlighted project efforts to help smallholder women diversify their farms with new crops, SI technologies and better market connections.

Production of grafted tomato plants represents a suitable, scalable, and sustainable SI technology for Cambodian smallholder farmers, especially women, with high potential for increased income through market engagement, as well as improved household nutrition.

Wild Gardens

Wild food plants (WFP), such as traditional and indigenous perennial vegetables, are critical components of the food system for many rural Cambodians. A rich diversity of highly nutritious, medicinal and/or economically useful species often function collectively within these homestead and village 'Wild Gardens'. Current efforts to understand, improve and disseminate this 'Wild Garden' system are inadequate. To optimize and fully leverage the potential of this novel food security and livelihood strategy, WFP need to be better characterized, and that knowledge needs to be integrated into Cambodia's agricultural education and training system. The WAgN project collaborated closely with the World Vegetable Center and ECHO Asia, focusing on characterization of WFP as a tool to diversify small farms and create improved income and nutrition opportunities.

A key to long-term sustainability of Wild Gardens as a supplemental food security system is linkage to markets. Project researchers conducted extensive wet and dry-season inventories of WFP present in Battambang and Siem Reap proviencesproduce markets. These surveys documented over 40 WFP species that have a strong market presence and command good-to-excellent prices. This 'market pull' is critical to system sustainability and the adoption of this SI technology by other farmers.

Smallholder farmer harvests Acacia pennata shoots from her 'living fence' in Battambang province, Cambodia. Photo credit: Ricky Bates.

This survey activity in the market also connected project researchers with farmers managing Wild Gardens on their small farms. It is clear from the respondents that Wild Gardens have a significant role that they play in household farming systems. Families use these plants in a variety of ways, with household consumption as the predominant use. However, farmers do report selling these plants for income, as well as saving money by using these WFP. Women are more likely to report that they use Wild Gardens as sources of medicine and food for animals, due to their greater responsibility for household members' health and caring for animals.

Our project results show that most WFP are part of the local informal seed system and generally not available for sale in formal markets. Germplasm inaccessibility and narrow distribution channels represent a constraint for the wider impact of this valuable resource.

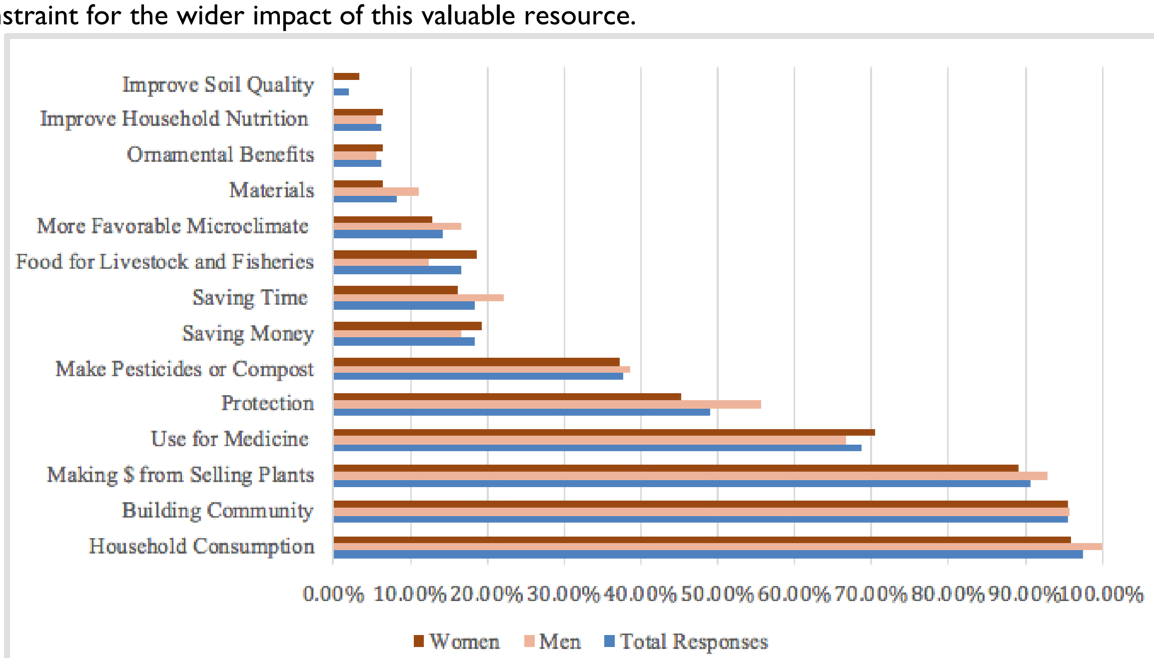


Chart 2: The WAgN project conducted extensive on-farm surveys and interviews with smallholder farmers managing to characterize their use of Wild Gardens, and the role they play at the village level.

A recent project activity involves implementing a new pilot program to connect with retail nurseries in Battambang and Siem Reap provinces. We are interviewing nursery managers regarding various aspects of their businesses and their experience with growing and selling WFP. Together with the ECHO Asia seed bank, we are exploring sustainable strategies to promote wider availability and distribution of WFP germplasm, which will be an important focus of future efforts to scale up Wild Garden adoption.

Wild Gardens are comprised primarily of perennial species, thus represent a low-maintenance alternative to traditional vegetable production. This is an important consideration for time-constrained single mothers, or in areas where the outmigration of working-age men is significant. Related to this dynamic, a University of Battambang Master of Sustainable Agriculture (MSA) student is conducting research that investigates the establishment of WFP under varying management regimes. Preliminary data confirms that after moderate inputs required for the first-year establishment, Wild Gardens are indeed low maintenance in terms of weed and pest management, fertilizer inputs and overall care.

WFP species hold untapped potential to improve household nutrition, especially the 'hidden hunger,' caused by a lack of key vitamins and minerals in the diet. The WAgN project in cooperation with Kasetsart University in Thailand, is systematically conducting nutritional analysis on key WFP, especially those for which there is no published nutritional data. Our nutritional data indicates that certain species of interest are high in key vitamins and minerals, and can serve as useful tools for combating malnutrition.

The WAgN project WFP proof-of-concept research has shown that Wild Gardens are suitable and sustainable SI technology. Constraints to scaling have been identified. Currently, local networks are being developed and research strategies proposed to shift this innovative food production system into wider use.

Cover Cropping

The WAgN project worked closely with CIRAD and the Conservation Agriculture Service Center (CASC) to research and implement several SI technologies. Key aspects of our collaboration focused on the use of underutilized cover and relay crop species, seed quality, and the informal seed system for underutilized agronomic crop species. Cover and relay crop research focused on soil fertility improvement, fodder source for cattle and seed production of cover crops. No-till planters and cover crops have been used on-farm with overall good results. The next steps will consider which process could support an uptake of these innovations at a larger scale.

Rice straw mulch is the product of choice for weed suppression and moisture conservation in our vegetable CA4SI (Conservation Agriculture for Sustainable Intensification) system. However, rice mulch straw and other alternative mulches are often in short supply as these are also used as livestock fodder. The WAgN project has initiated activities to partner with Dr. Florent Tivet's CIRAD team to develop living cover crop systems suitable for smallholder vegetable production. We envision cover-cropping systems that will provide suitable weed suppression and moisture conservation on par with straw mulch, but would have the added benefit of soil building and N fixation.

Obejctive 2: Identify and Foster Enabling Conditions and Social Networks for Women to Fully Participate in the Local, Regional and International Value Chains for Horticultural and Rice-Based Foods Produced by SI

The activities in this objective help identify norms that limit the participation of women in various agricultural sectors and in leadership positions.

Leadership

Women play a significant role in agriculture in Cambodia. Traditionally responsible for growing staple foods, 62 percent of women are engaged in the production and marketing of crops they produce, and women represent 70-80 percent of vegetable dealers. However, women's workload includes domestic responsibility which increases their time burden. This limits their time for crop production, training and other activities needed for true empowerment. This affects family nutrition, food production and food security, especially in regions where women take on primary roles as smallholder producers.

The International Food Policy Research Institute implemented the Women's Empowerment in Agriculture Index (WEAI) in Cambodia, which measures five domains of women's and men's involvement in agriculture, including decision making in agricultural production, access to and control over resources, control over income, leadership in the community and time allocation. Their results showed that women face three significant sets of constraints - group membership (and leadership), workload and access to credit. As this suggests, women continue to face serious barriers to achieving empowerment. The WEAI data suggest comparatively strong possibilities for Cambodian women to take leadership in SI and gain access to value chains. The WAgN project used a gender-sensitive lens to analyze SI and come up with recommended strategies to encourage the use of innovative SI technology/practices that will enhance women's participation in value chains.

WAgN researchers addressed the topic of gender in a variety of ways. To build capacity regarding gender and agriculture, two female graduate students were involved in the gender aspects of the WAgN project. One student, Sovaneary Huot, focused on the barriers to leadership opportunities. Her work highlights the division between men and women regarding leadership positions. Women are often not represented in leadership roles and while the reasons for this vary, some main factors include the lack of education for women. The female farmers in the project responded that they feel their capacity is limited and that they would not make good leaders. This is related to their expectations that a leader needs specific bookkeeping skills along with reading and writing proficiency. Many women do not finish primary school and thus feel like they are ill-prepared for leadership.

Another major factor is that women are often the caretakers of the family, as well as producers of horticultural products. Women have to take care of children and domestic duties as well as grow vegetables and often market them. They do not have time to be leaders of organizations especially since the work as leaders is usually not compensated. More generally, it is not traditional for women to be leaders in Cambodia. They often play a background role and are not the ones to speak in public. The WAgN project has been working with cooperatives and agricultural organizations in Battambang and Siem Reap to understand the cultural constraints faced by women in agriculture.

> Promising results were obtained from on-farm demonstration, in terms of their capacities to adapt to a wide range of soil and water recession dynamics, while effectively restoring soil fertility.

Adoption of SI Practices

The other graduate student, Emily Southard, focused on identifying barriers to and opportunities for women's adoption of SI technologies and practices. Her findings show there is some division of labor between men and women in terms of women being largely in charge of domestic labor and vegetable cultivation, and men being largely in charge of rice cultivation. However, this division of labor was described as very flexible, and both responses and observations confirmed that it is not uncommon for men to assist women in domestic work and vegetable cultivation, nor is it uncommon for women to assist in rice cultivation. The most highly gendered tasks were those that were considered very physically demanding; cultivating land, using heavy machinery, and operating irrigation pumps were all gendered towards males due to the physical power they required. However, some women expressed with pride that they were able to do these jobs, suggesting that gender transgression was seen as empowering.

In households where the marital relationship was more equitable and labor was shared between spouses, it was expressed that men and women both have equal leisure time. In households where men were a more dominating force, women were seen as having less leisure time, with complaints about men spending time drinking with friends. In terms of labor, men were seen to have harder work to do, as it is often physically demanding. Women were seen as working more hours in a day, but it was perceived that work was less demanding as it was seen as less physically taxing.

Local definitions of empowerment were closely linked to success as a farmer and an ability to earn income through selling produce.

Income was frequently mentioned as the most important marker of a woman's empowerment. Intelligence in managing a household and carrying out domestic duties were also often mentioned. However, disempowered women were typically described as those women who only carried out domestic duties such as cooking, cleaning and caring for children, but did not participate in agricultural work and sales. Some women described themselves as disempowered as they had young children and were currently unable to engage in productive and income-generating labor.

Decision-making was typically described as being shared between men and women, and it was common for households to describe women as having the final decision-making power. However, it was described that in day-to-day decisions, such as financial decisions, women have the power, but in large decisions, there needs to be a conversation between spouses. For instance, it was expressed several times that if a woman were to buy a piece of land or a motorbike without first discussing with her husband, it would be a major source of conflict and potentially domestic violence.

Marketing

Farmers were surveyed to identify barriers for them to access markets. They reported multiple barriers to increasing their market participation (see table below). Approximately 80 percent of farmers surveyed (N=394), reported that the low prices for vegetables are the largest barrier to participation. This makes sense, as farmers are competing with vegetables imported from neighboring countries. Additionally, consistently producing high-quality vegetables remains a struggle for many farmers as they often do not have access to high-quality inputs. Temporal challenges remain as the production of vegetables change throughout the dry and wet season. The SI technologies highlighted, vegetable grafting and wild gardens, have the potential to address these temporal challenges by extending the production seasons or providing different products.

Category	Percent of producers reporting barrier
Low price (low-profit potential)	80
Vegetable quality	20
Lack of transport	13
No time to produce or market	12
Struggles with continuous supply	7
Location (distance from the market)	3
Other	6

For vegetable sales at local markets, the trading was described and observed to be dominated by women. Women were perceived as being better suited to working with customers. This was described both because women's nature was better suited to interacting with customers and because women primarily are responsible for shopping, and thus are more skilled at haggling. Men are engaged in the vegetable trade as well but not typically on the customer service end. Women described they could be more successful if their husbands or other male kin assisted them in vegetable trading because men are physically strong. Thus, men's skills are typically applied to transporting goods, at the farms themselves and then unloading at the markets and delivering goods to customers. On their own, women didn't feel capable of transporting their goods from one market to another, but several participants able to transport their goods to two different markets if they were assisted by male kin.

Selling vegetables was seen as a trade that is easily accessible to women and provides them an opportunity to earn an income on their own. While the most profitable traders work with male kin, female traders may also work alone and be divorced, single, widowed, or elderly. Some women even discussed selling vegetables when they were small children to pay their school fees. Respondents suggested that for uneducated women, this was the best way to earn an income and that you only need a small initial investment to begin a vegetable selling venture. Moreover, respondents suggested selling vegetables was superior to the other two income-generating options they saw for uneducated women: farming or working in Thailand (in factories). Farming was described as more physically demanding than selling vegetables and also more dependent on male kin to do physical work. Farming was seen as almost impossible for single/divorced/widowed women to do on their own because of the need to plow, use machines, etc. Vegetable sellers found this work to be superior to working in Thailand because they had more freedom and were closer to their families and communities.

Vegetable selling was seen as a pathway to empowerment and those who sold vegetables frequently described themselves as empowered. However, similar to with farmers, if women were not successful in their sales they did not see themselves as empowered. Empowerment was closely associated with their conceptualization to success. Moreover, several women expressed they would rather work in an office or business environment if they were qualified, or not work at all if their family had enough wealth. While they described themselves as empowered, they also described themselves as unlucky to have to do this work and envious of wealthier and more educated Cambodian women.

Major challenges that vegetable sellers reported included challenges in profit margins, challenges in competing and selling their vegetables, physical challenges of transporting produce, and the time demands of the work. For farmers selling Cambodian produce, profit margins were slim compared to those competitors selling more inexpensive Thai and Vietnamese produce. Some sellers complained they are not always able to sell all their produce, causing it to rot and them to lose money. Cambodian produce was reported to rot quicker than imported produce. For women working alone, the physical challenge of moving goods was often reported. Lastly, many sellers worked from 4 AM until the evening. For mothers, this was particularly challenging. Some brought small children to the market with them, while others had kin watch their children for them. This caused some gender transgression, as for one trader we talked to, her husband now stayed at home watching the children, cleaning and cooking, which are all considered more gendered feminine tasks.

When asked how government and NGOs could support sellers, suggestions included to promote Cambodian produce, to provide training days that bring together farmers and sellers, and to provide training for women to improve their marketing and sales skills. Women who had independently entered sales felt that NGOs or government could provide training to help women like them learn skills to be successful.

To address these needs, we provided training in conservation agriculture in collaboration with the World Vegetable Center and their ongoing work in Siem Reap. ADDA as well used WAgN funds to train women farmers in improved household vegetable production.

We worked with Oxfam, ADDA, and the World Vegetable Center to provide leadership training to a variety of female farmers and key stakeholders and community leaders. We supported work on Conservation Ag work with Soil health and training on soil conservation.

Objective 3: Build Capacity in Local Agricultural Institutions, NGOs, and International Universities and Research Institutes, to Scale Up and Out Innovations in Gender and Ecological Sensitive Sustainable Intensification

The WAgN project realized the significant capacity-building impact on a variety of fronts during the life of the project.

Channaty Ngang successfully defended her MSA thesis at the University of Battambang (UBB), with Dr. Bates serving as major advisor. Dr. Bates also serves as a major advisor for MSA students Biya Chhorn and Chantha Thay, who are currently conducting research at UBB on tomato grafting and wild food plants, respectively. The WAgN project also supports Saren Ry who is working toward his B.S. degree at UBB. Six undergraduate and graduate students under the direction of Dr. Sudathip Sae-than received short-term training on nutrient analysis of WFP at Kasetsart University.

Drs. Rick Bates and Dave Ader contributed to the CE SAIN lecture series on separate visits to the Royal University of Agriculture (RUA). The WAgN project PIs visited with CE SAIN staff to develop strategies to demonstrate SI technologies focused on income generation and nutrition. Tomato grafting demonstrations were established at CE SAIN tech parks in Battambang, Siem Reap, Kampong Thom and RUA.

The WAgN project Co-PIs, Ader and Gill, were able to build on the work to secure additional funding through the USAID Livestock Systems Innovation Lab to examine underutilized WFP useful as animal fodder. They were able to work with CE SAIN and UBB to work on-station at the CE SAIN tech parks, and on-farm with farmers in Battambang.

The WAgN project PI Rick Bates worked closely with ECHO Asia and CIRAD staff to facilitate seed saving/seed quality workshops hosted at the Bos Khnor research station in Kampong Cham and the Upland Wholistic Development Center in Mae Ai, Thailand. WAgN resources and expertise also assisted with the improvement of seed handling and seed storage facilities at the Bos Khnor research site. Project personnel also assisted ECHO Asia in the development of a new WFP nursery and demonstration site at their new research farm outside Chiang Mai, Thailand.

The WAgN project was instrumental in forming a relationship between UBB and PSU, which led to PSU entering into a partnership agreement with UBB to assist in the implementation of the new World Bank Highter Education Improvement Project (HEIP.) The mission of the World Bank HEIP is to enhance the quality and improve the capacity of the University of Battambang regarding teaching and learning in science, technology, engineering, mathematics (STEM) and agriculture. A UBB-World Bank team made a visit to PSU in April 2019.

The WAgN project was instrumental in forming a relationship between PSU, the University of Tennessee (UT) and CE SAIN, which led to CE SAIN and UT entering into a partnership agreement with the USAID Farmer to Farmer program (F2F), to provide capacity training for farmers and farm organizations in Cambodia with the help of American farmers.

ECHO Asia, with funding from WAgN, translated four publications from English into Khmer.

Dr. Rick Bates was awarded a Fulbright scholarship to Cambodia, hosted by the University of Battambang (Nov. 2019-June 2020). This award was a direct result of the UBB-Penn state relationship established via the SIIL WAgN project. The Fulbright at UBB will engage graduate students, support graduate instruction and continue certain lines of WFP research initiated under the WAgN project.

Objective 4: Test the SI Assessment Framework in Alignment with Project Objectives and/or Activities

There is a need to translate the general principles of sustainability into operational definitions and practices. The SIIL creates the Sustainable Intensification Assessment Framework to provide a set of indicators organized into five domains considered critical for sustainability, namely productivity, economic, environment, human condition and social domains. The primary purpose of the Sustainable Intensification Assessment Framework is to strengthen researchers' ability to holistically assess the performance of an innovation in terms of the direct and indirect consequences within and across domains. We use the assessment framework to evaluate SI technologies (vegetable grafting and wild gardens,) to determine their effectiveness. Wild gardens have the potential to produce an abundance of food sources with relatively little labor or time inputs for their management, which is favorable given existing time constraints women face. In addition, as they are under women's general domain, WFP has the economic potential to serve as a source of income for women. To discuss Wild Gardens as a potential SI strategy, we posit it is imperative to consider women's roles, time, and influence in their management and use, to optimize their potential in yielding livelihood improvements.

We analyzed the role of gender across all five categorical domains of the assessment framework, utilizing results from small-scale agricultural households in Northwest Cambodia and measuring the potential of SI for wild gardens and grafting. We found that Wild Gardens management and use have gendered implications that promote gender equity across all indicators, not only the social domain under which it is housed. For example, while some male household members, often elderly males or children, participate in Wild Garden management, it is primarily the women's domain. Women primarily make decisions about which plants to grow and are responsible for the maintenance, harvesting, use and selling of the plants. Wild Gardens provide supplemental sources of food, nutrients, income, shade, and raw materials that women need and use to maintain the wellbeing of their households. The Wild Gardens are maintained around the household, which does not incur any travel costs, and additionally saves women from having to travel to the markets to shop for household food or raw materials. Also, as Wild Gardens' maintenance requires little to no labor or time investment, it does not add additional burden to women's time, often seen in well-intentioned development initiatives.

7. Utilization of Research Outputs

The use of various outputs and information from the WAgN project have been used to inform meetings with provincial departments of agriculture and the MAFF. They have then developed the Conservation Ag service with a fee, and the consortium on Conservation Agriculture.

We have utilized data from replicated tomato grafting experiments to elucidate eggplant rootstock-tomato variety combinations which impart a high degree of disease and abiotic stress tolerance under Cambodia rainy-season conditions. These results have been used to develop recommendations for commercial and/or smallholder farmers, and have been shared with key governmental and NGO stakeholders.

Wild Gardens' proof-of-concept research has allowed the WAgN project to develop a robust characterization of the role wild food plants play in the Cambodian food system. This analysis has documented income generation from market linkages, nutritional profiles for key species, and the role of gender in the management of this underutilized food system. These results form the basis of future research to target WFP constraints and opportunities for improved nutrition and income generation on a wider scale.

8. Future Challenges and Opportunities

Challenges

Challenges identified by WAgN involve various scales and domains. Often challenges at the farm level are easier to resolve than those at a national level. However, possible solutions and opportunities remain.

- In Battambang and Kampong Thom proviences, several fields with cover crops were lost due to the burning process at night for hunting purposes. These issues emphasized the need to strengthen collective action that should bring together not only targeted communities, but also neighboring communities and the need for a clear economic model giving value to the cover crops used. This is challenging, and despite the progress made with the use of simulation games and participatory process, there is still a range of issues that have to be overcome. This result emphasized the need to invest in an assessment of the value chains of seeds of cover crops and/or other crop diversification processes to bring immediate return (cash) to farmers.
- A challenge to scale up SI technologies is the lack of an established system for linking project technologies such as containerized grafted tomatoes, to retail markets like stores and nurseries.

> Cover crop seeds relate to the larger challenge of contraints in the acquisition and propogation of WFP germplasm. Without the availability of planting material (seeds, cuttings or transplants,) it is difficult to scale-up impacts of WFP.

- Lack of integration of cooperatives into research and collective action is another challenge WAgN faced. Cooperatives could be ideal organizations with which we can scale technologies, as they already have market access. Working with ADDA and the various USAID projects (HARVEST II) could be a way to engage them more.

- Another challenge is how youth out-migration is eroding the knowledge of WFP. Knowledge is often traded and shared in communities along with germplasm however, with youth leaving rural areas, the knowledge of traditional and wild plant species and their uses, is at risk of being lost.

Opportunities

- **Develop tomato grafting and wild food plants modules compatible with STEM+Ag training in schools:**

Partnering with CE SAIN technology parks located at high schools provides a unique opportunity to enhance curriculum and work with new initiatives such as the SEARCA school-home garden project. This general concept has been proposed to high ranking officials within the Ministry of Education, Youth and Sports and has received strong support.

- **Work with cooperatives to expand models of grafted vegetables for temporal diversity**:

Cooperatives could produce the grafted plants, and then provide plants to members who would contract to produce vegetables for the markets. They could also sell the grafted plants or work with nurseries to sell them. We are currently in discussions with Swisscontact to develop plans to engage the private sector to market containerized grafted tomatoes. Partnering with ASMC and tomato transplanting machinery could allow for tomato grafting technology to be deployed at a commercial scale.

- **Working with SOILS consortium on additional plants to incorporate into systems to improve soils and use as cover crops for vegetable gardens:**

Mulch is often promoted for conservation agriculture, but mulch is mostly rice straw and is limited especially during the dry season. Other plants exist that could be used for mulch that would not compete as fodder. We are expecting to continue our partnership with CIRAD to develop cover crop systems for vegetable gardens, which will employ a dual-purpose cover crop system for weed suppression and soil health enhancement.

9. Publications

1. Eissler S., D. Ader, T. Gill, S. Huot, and R. Bates. 2019. Taming the messy fringes: wild gardening as a Sustainable Intensification strategy. International Journal of Agricultural Sustainability. (Submitted)

a. Hav K., C. Ngang, P. Srean, D. Ader, and R. Bates. 2020. Rainy-season performance of tomato grafted onto eggplant rootstocks in Cambodia. (Manuscript in preparation – expected submission January 2020)

2. Bates R., D. Ader, T. Gill, and S. Brown. 2020. Role of underutilized wild food plants in small farm diversification in northwest Cambodia. (Manuscript in preparation – expected submission March 2020)

10. Datasets Produced

Multiple datasets were created as part of the WAgN project. These various datasets have been cleaned and uploaded into the SIIL Harvard Dataverse (see table below for more detail).

Dataset	Repository	Notes
WAgN and ASMC Household Survey	SIIL Dataverse-Unpublished	This was collected jointly by WAgN and ASMC.
Conservation Agriculture - Soil Fauna	SIIL Dataverse	This data is connected to CIRAD and UBB masters student research.
Soil Health Improvement	SIIL Dataverse	Data connected to CIRAD and UBB.
Tomato Grafting	SIIL Dataverse	Data come from experiments in Siem Reap and Battambang.
Wild Gardens Household Data	SIIL Dataverse	Survey data from Battambang.
Agriculture Cooperatives and Leadership	Data have not been uploaded to the Dataverse as they are transcribed interviews.	Qualitative Data from Cooperative Surveys and Focus Groups.
Nutritional Analysis of underutilized vegetables	SIIL Dataverse	Data come from a nutritional analysis of various wild food plants at Katsetsart University, Thailand.
Wet-season market data for underutilized plants	SIIL Dataverse	Data collected from surveys of markets in the wet season.
Market data for Horticultural Species	SIIL Dataverse	Data collected from a survey of markets in the dry season.
Youth Migration	SIIL Dataverse	Data collected from students in Phnom Penh at the Royal University of Agriculture.
Wild food plant nursery survey	SIIL Dataverse	Data collected from a survey of plant nurseries in Siem Reap and Battambang.

CONSORTIUM I

geospatial and farming systems research

Consortium I

Geospatial and Farming Systems Research

1. **Lead Institution:** University of California Davis (UC-Davis)
   - U.S. Collaborating Institutions:
     - Kansas State University (KSU)
   - International Collaborating Institutions
     - (see GFC site from SIIL site)

2. **Research Team:**
   - Lead Investigator:
     - Robert J. Hijmans (UC Davis)
   - Co-Investigators:
     - Aniruddha Ghosh, UC Davis
     - Alex Mandel, UC Davis

3. Executive Summary

In 2014, the Geospatial and Farming Systems Research Consortium (GFC) was established at the University of California, Davis with support of the Feed the Future (FtF) Innovation Lab for Collaborative Research on Sustainable Intensification (SIIL) to integrate various approaches for agricultural development using a spatial framework and study the dynamics of farming systems, particularly for the smallholder farmers in Asia and Africa. The GFC adopted a holistic framework to combine different components of the farming systems, through a portfolio of research subawards and independent research projects. We have developed more than 25 collaborative projects across multiple countries that included both SIIL as well as FtF focus countries. Our collaborators have used established and cutting-edge research methods and tools that include advanced spatial modeling, big data analytics, machine learning, standardized household surveys, laboratory analysis, field trials, large scale field data collection, satellite remote sensing, unmanned aerial vehicles and ground sensors to solve critical challenges in the domain of sustainable intensification. Over the last five years, we conducted multiple workshops in international locations to train more than 250 participants from government, academic and private sectors. We developed country profiles and online data portals for SIIL focus countries, free and open-source software, and guide materials to support open science and research in the field of agriculture.

> Overall, the GFC has helped to establish a novel platform connecting isolated components of the farming systems that brought together leading researchers from worldwide institutions to address the complex challenges faced by the smallholder farmers and target, design and develop the most effective interventions for a sustainable food secure future.

4. Project Partners

The consortium is led by Dr. Robert Hijmans at the University of California, Davis (UC Davis) and included collaborators from U.S. universities, international research organizations, regional institutions and private organizations. Names of the project partners are mentioned below.

University Of California Davis Partners

Department of Agriculture and Resource Economics
Department of Land, Air and Water Resources

Department of Nutrition
Program in International and Community Nutrition
University of California Agriculture and Natural Resources
UC Davis Drone Club
UC Davis Russell Ranch Sustainable Agriculture Facility

U.S. Universities

Arkansas State University
Duke University
Harvard University
Stanford University
University of Arkansas
University of Maryland

International Research Organizations

International Institute for Applied Systems Analysis (IIASA)
Centre de coopération internationale en recherche agronomique pour le développement (CIRAD)
Institut de Recherche et de Développement (IRD)
International Center for Tropical Agriculture (CIAT)
International Food Policy Research Institute (IFPRI)
International Institute of Tropical Agriculture (IITA)
International Livestock Research Institute (ILRI)
International Maize and Wheat Improvement Center (CIMMYT)
World Agroforestry Centre (ICRAF)

Regional Institutions

Bangladesh Agriculture Research Institute (BARI)
Centre National de Recherches Agronomiques (CNRA-ISRA)
Institut Sénégalais de Recherches Agricoles (ISRA)
KIFIYA Financial Services
Laboratoire National d'Etudes et de Recherches Vétérinaires (LNERV-ISRA)
Laboratoire National de Recherche sur les Productions Végétales (LNRPV-ISRA)
One Acre Fund (1AF)
Regional Centre For Mapping Resource for Development (RCMRD)
Regional Centre for Plant Drought Adaptation Study (CERAAS-ISRA)
Royal University of Agriculture, Cambodia
Royal University of Phnom Penh, Cambodia
University of Twente (ITC-Netherlands)

Private Organizations

Crop Nutrition Laboratory Services Ltd (CROPNUTS)
DigitalGlobe
Pix4D
QED (qed.ai)

5. Project Goals and Objectives

Overall Goal

The overall goal is to aim to explore and improve approaches for understanding the dynamics of farming systems using a spatial data analytics framework.

Overall Objectives

Our efforts, through a portfolio of research subawards and independent research, focused on the following four primary objectives to accomplish the goal:

Objective 1: Identify patterns of intensification & opportunities for sustainable intensification (SI)

Objective 2: Study the relation between SI and nutrition, socio-economic and environmental outcomes

Objective 3: Develop open data and tools for agricultural development

Objective 4: Organize workshops/courses and prepare web-based material on spatial data analysis for agricultural development.

6. Overview of Activities & Accomplishments

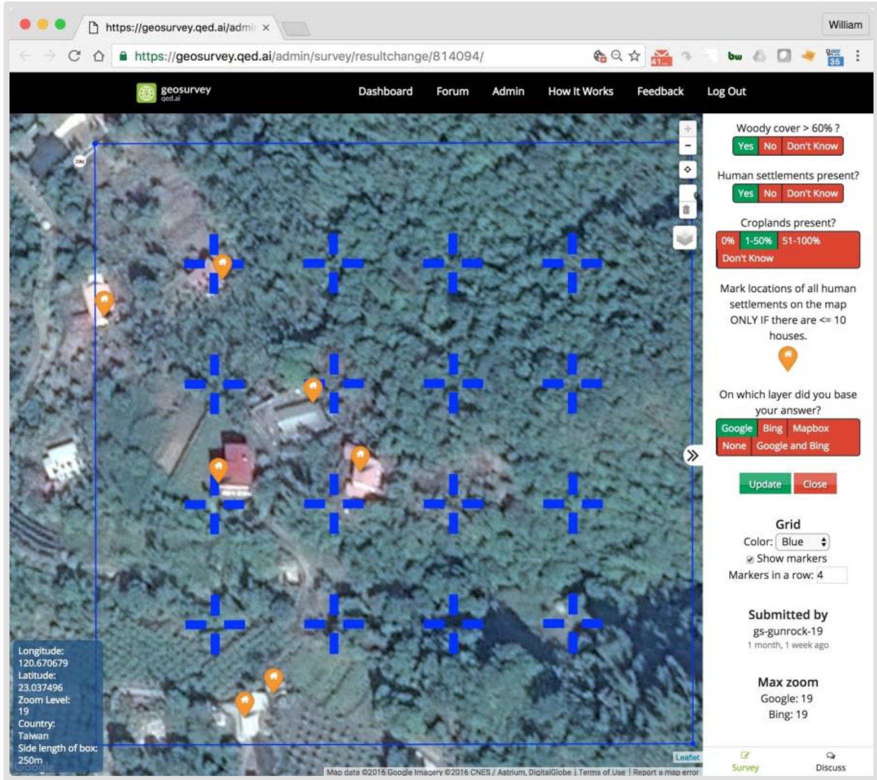
Between 2014 and 2019 the GFC designed and launched more than 25 collaborative projects, the majority of which have been completed. Activities and achievements under these projects are described below.

Objective 1: Identify Current Patterns Of Intensification And Opportunities For Sustainable Intensifications

Project 1: Open access database of cropland locations using high-resolution satellite data

This project was implemented by QED Inc., in close collaboration with the GFC members. We analyzed the satellite imagery of almost 500,000 locations around the world through the Geosurvey crowdsourcing platform (https://geosurvey.qed.ai/about/). A list of (latitude, longitude) pairs for conducting Geosurveys, spanning 498095 points and 61 countries in total, along with 2000 validation data points were used. For each country we launched a separate Geosurvey, working in alphabetical order given that country's ISO ALPHA-3 code. Questions were posited for 250m-by-250m quadrilateral grids whose centers were given by the original list of (latitude, longitude) pairs. This analysis included quantitative classifications of croplands, woody cover, and human settlements. Before starting on any Geosurvey, each Geosurveyor was required to study the Land Usage Guide, which is shared publicly at the following link: *Geosurvey: Land Usage Guide*. The construction of this guide was a collaborative effort with the GFC staff. After each country's Geosurvey, team leaders randomly subsampled 7% of the total points from that survey to estimate accuracy. A total of 36924 points were randomly selected for this auditing, and amongst these points, the overall accuracy is estimated at 92.6%. Many updates are in the pipeline for Geosurvey's development. Some examples include:

- The back-end and front-end are being rewritten to be more scalable, such that larger numbers of users can be supported for future gamification campaigns.
- Data sharing with Geosurvey should be easier, such that users can more easily share these results. This is also related to controlling scalability carefully since administrators can consume far more computational resources than regular users.
- We have built the Geosurvey Collect mobile app, now available in the Play Store, that allows users to stream pictures from their mobile phones into Geosurvey for crowdsourced tagging and classification. Applications include crop mapping, crop health monitoring, and validation of Geosurvey answers with on-the-ground validation data.

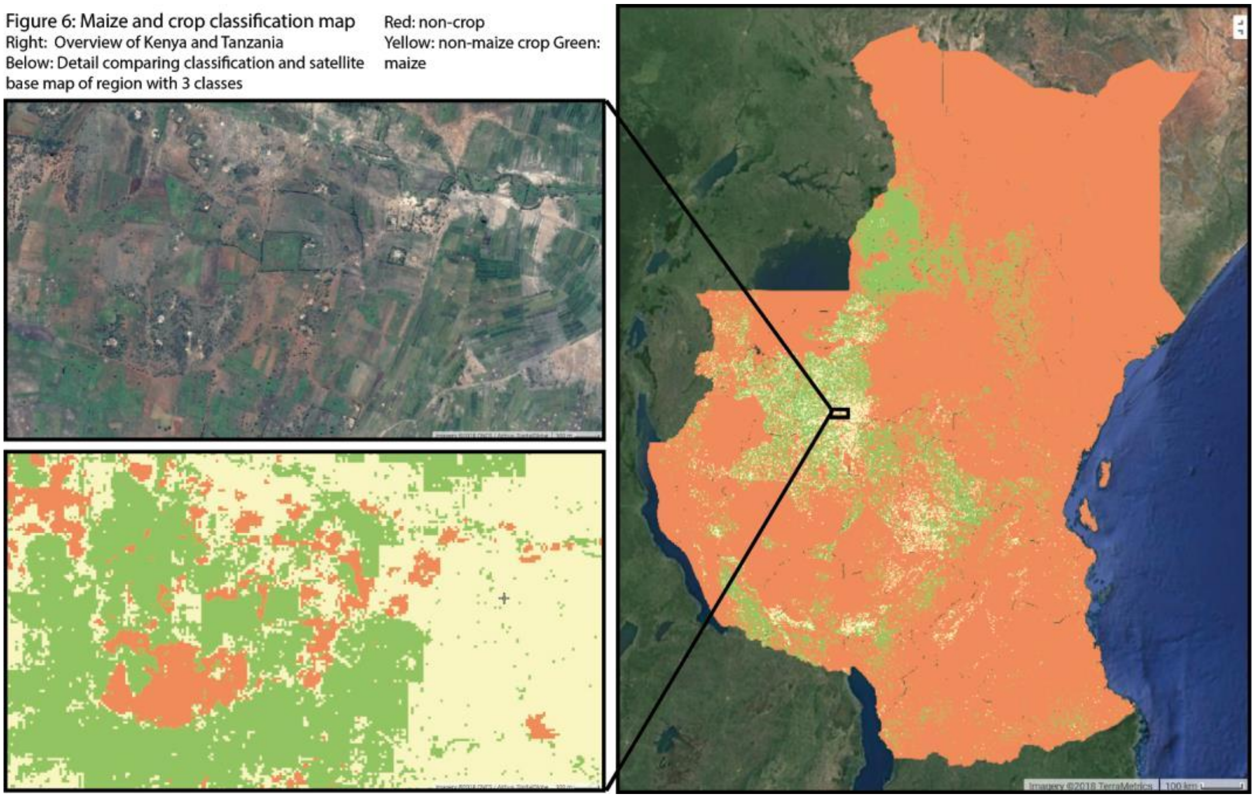


Geosurvey interface as used for this survey

Project 2: High spatial resolution information on crop growing areas in Tanzania, Bangladesh, and Cambodia

2.1. Map maize growing areas in East Africa

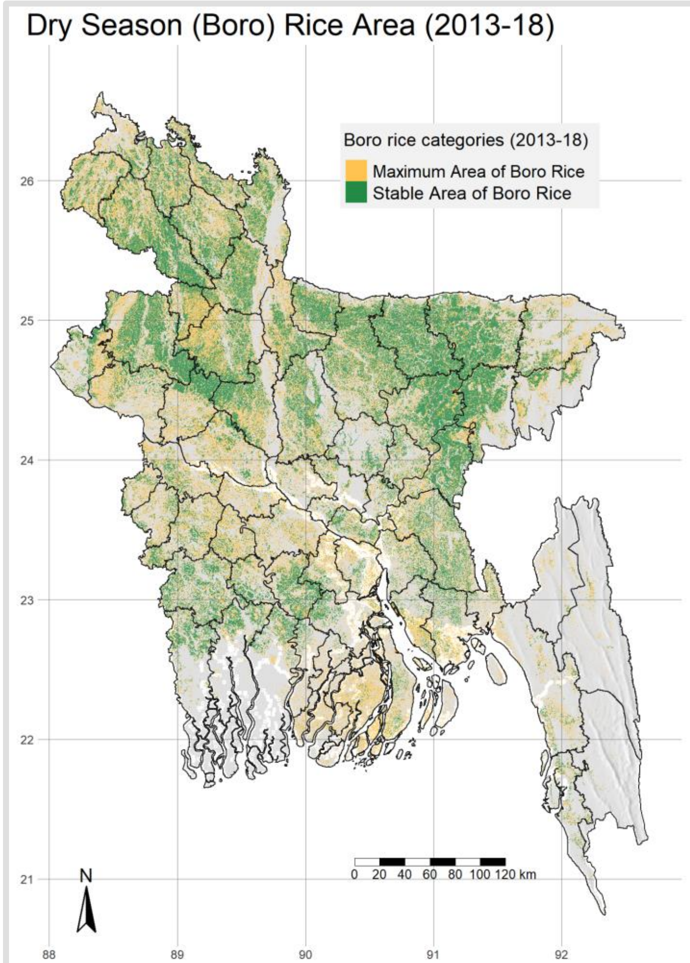
This project was implemented by Stanford University in close collaboration with the CIMMYT, University of Maryland and One Acre Fund. We approached our goal of identifying maize pixels as split into two tasks: one to distinguish cropland pixels (CRL) from non-crop pixels, and one to identify maize pixels (MZL) from other types of crop pixels. Although our final goal was to generate the MZL map, we chose to first generate a CRL map to isolate crop pixels and reduce the overall intra-class variance in the MZL classification process. Both of these classifications were based on seasonal median composites of Sentinel-1 and Sentinel-2 data, with three seasons defined as (i) October-January, (ii) February-May, and (iii) June – September. Even though median composites reduce problems with clouds if there are sufficient numbers of clear scenes, we found it necessary to first improve the cloud mask in Sentinel-2 images. To do this, we identified several hundred locations with clouds, haze, cloud shadows, and clear conditions for imagery collected in the region throughout 2017. We then developed both random forest and simpler decision tree models to develop a new cloud mask, which proved better than the pre-existing mask.



Study region of Kenya and Tanzania showing classification map of maize (green), non-maize crop (yellow) and non-crop (red) locations, based on random forest applied to Sentinel-1 and Sentinel-2 seasonal composites.

2.2. Map 'boro' rice-growing areas in Bangladesh

This project was implemented by the University of Arkansas and GFC team members. We demonstrated a new method to map paddy rice using Google Earth Engine (GEE) and the Landsat archive in Bangladesh during the dry (boro) season. Using GEE and Landsat, dry season rice areas are mapped at 30 m resolution for approximately 90,000 km2 annually between 2014 and 2018. The method first reconstructs spectral vegetation indices (VIs) for individual pixels using a harmonic time series (HTS) model to minimize the effect of any sensor inconsistencies and atmospheric noise and then combines the time series indices with a rule-based algorithm to identify characteristics of rice phenology to classify rice pixels. To our knowledge, this is the first time an annual pixel-based time series model has been applied to Landsat at the national level in a multi-year analysis of rice.



Findings suggest that the HTS-VIs model has the potential to map rice production across fragmented landscapes and heterogeneous production practices with comparable results to other estimates but without local management or in situ information as inputs. The HTS-VIs model identified 4.285, 4.425, 4.645, 4.117, and 4.407 million rice-producing hectares for 2014, 2015, 2016, 2017, and 2018, respectively, which correlates well with national estimates from official sources at an average R-squared of 0.8. The dataset has been submitted in the dataverse.

Project 3: Comprehensive field boundary information across a diverse and representative set of croplands in specific areas of SIIL focus countries

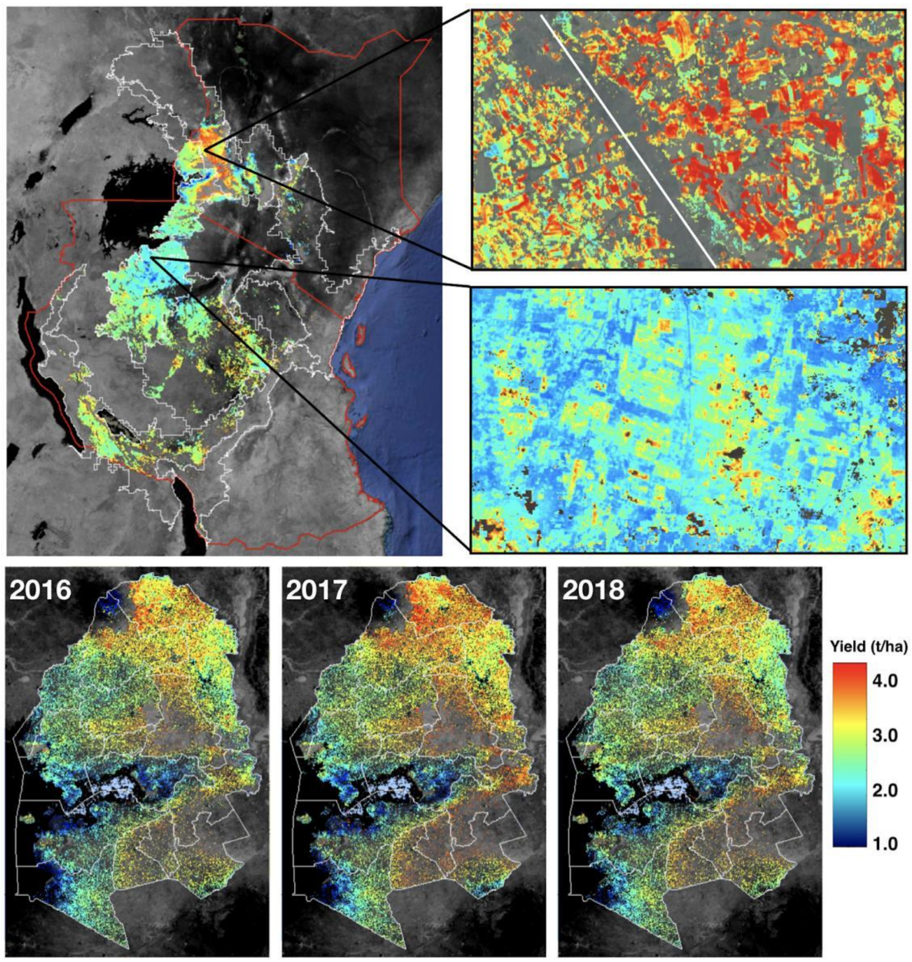
This project was implemented by the Faculty of Geo-Information Science and Earth Observation of the University of Twente (ITC-Netherlands), in close collaboration with International Institute for Applied Systems Analysis (IIASA), KIFIYA Financial Services, and GFC members. This study used high spatial resolution imagery within an online digitizing tool and trained users to manually digitize field boundaries from those images. This resulted in a unique crowdsourced database of over 7,000 field boundaries in the Amhara highlands and Oromia region of Ethiopia. Two semi-automated field boundary mapping techniques (gPb and eCog) were applied to the same imagery and the resulting boundaries were compared against the manually digitized boundaries. Overall, eCog over-segmented but generally had lower location-accuracy, while gPb under-segmented, but had higher location accuracy. We recommend eCog as the superior approach for field mapping since it captures boundaries that represent objects at the field level whereas gPb seems better at capturing boundaries for larger agglomerations of fields and may be suitable for cropland extent mapping. The current processing chains for both methods require some user skill in parameter choice and there is a need to improve the batch processing capability and to derive guidelines for parameter pre-selection based on image and terrain characteristics. Quality control of the manually digitized boundaries was an issue that required lengthy data preparation and processing. The study demonstrates the challenge of applying semi-automated techniques to highly variable, smallholder farming systems in Africa where field sizes are small, prior information is poor and where boundaries are unclear. We see opportunities for these methods and their processing chains to be improved in future work. Our recommendations provide some points of departure for further research on the applicability of these methods before they can be considered for operational use.

Reference boundaries (a) and outputs from the two boundary detection methods, gPB (b) and eCog (c), for one 1 km × 1 km tile in the Amhara Region

Project 4: Scalable method to estimate crop yield and in-season crop yield forecasts
This project was implemented by Stanford University in close collaboration with the CIMMYT, University of Maryland and One Acre Fund (1AF). This project focused on developing and testing procedures to estimate maize productivity in eastern Africa. This information is central to better understanding the current level of intensification in maize systems and the constraints to raising the system's productivity. The approach leveraged newly available imagery from the European Space Agency's Sentinel-1 and Sentinel-2 satellites, ground data on crop locations and yields, and a new simulation-based approach to estimating maize yields anywhere in the world. Results showed considerable success in mapping both where maize is growing and how productive it is.

The yield mapping approach we use relies on model simulations rather than ground data for calibration, which makes it a much more flexible and scalable approach than other methods. However, generating these simulations takes a significant amount of effort to make sure the input data on soils, management, and weather are reliable. We first randomly sample points within each region based on existing maps of where maize is grown, with a stratified random sample to ensure we get sites across a range of temperatures. For each site, we then specify soil profiles based on FAO soil grids. For management, we run various combinations of fertilizer (0, 25, and 50kg), sowing density (3, 4, and 5 plants per m2), initial soil water (60%, 80%, and 100% moisture), and sowing dates at each site, with three different sowing dates centered on the FAO estimated green-up date for that site (which is based on analysis of AVHRR satellite data). These simulations are then grouped for all sites within a common zone according to the new Global Agro-Environmental Stratification (GAES) maps (Mucher et al. 2016).

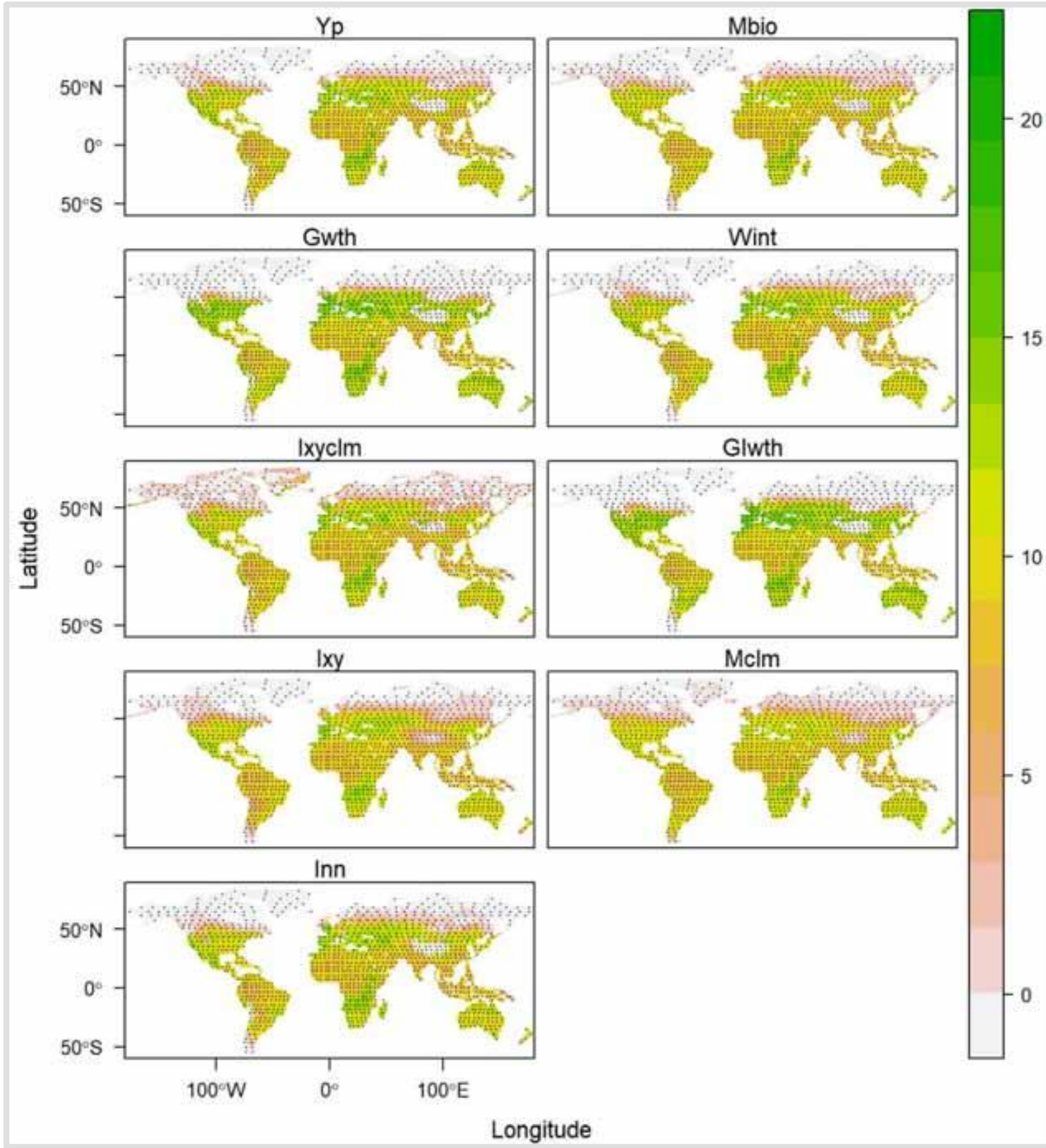
To estimate yields, the simulations described above were used to develop regressions that predict yield Y as a function of various observables X. These observables are typically vegetation indices that we calculate from simulated crop variables such as leaf area index (LAI) or total canopy nitrogen (TN). In some formulations of SCYM, we use these observables on the actual dates of image observation for each pixel. In other versions, we fit a harmonic regression (a sum of sin and cosine functions of time) to the data and use values derived from the fit of these regressions, such as the peak value during the season and the inferred sowing date. To evaluate the yield estimates, we aggregated them to the district level and compared them with aggregated crop cut data for maize yields by 1AF. The agreement with 1AF is quite good, especially when the yield estimates are based only on simulations from sites in the local area of the 1AF region (Western province) rather than sites from the entire GAES zone. Future work will focus on applying these datasets to understand drivers of maize productivity in the region.



Study region of Kenya and Tanzania showing estimated maize yields for 2017, including detail for two sub-regions (top) as well as yields for 2016-18 for the Western province in Kenya (bottom)

Project 5: Maize yield potential using different modeling approaches

This project is implemented by UC Davis. Opportunities for and constraints to crop production can be assessed with crop growth simulation models. Most crop simulation models require daily weather data as input, but such data are generally not available at a high spatial resolution. Several approaches have been developed to estimate yield potential (Yp) at locations without daily weather data (weather stations) but these have not been compared. In this project, we used two crop simulation models (WOFOST and LINTUL) to compute Yp for two crops for the entire world. A global weather database was divided into 856 training and 12,808 testing sites.

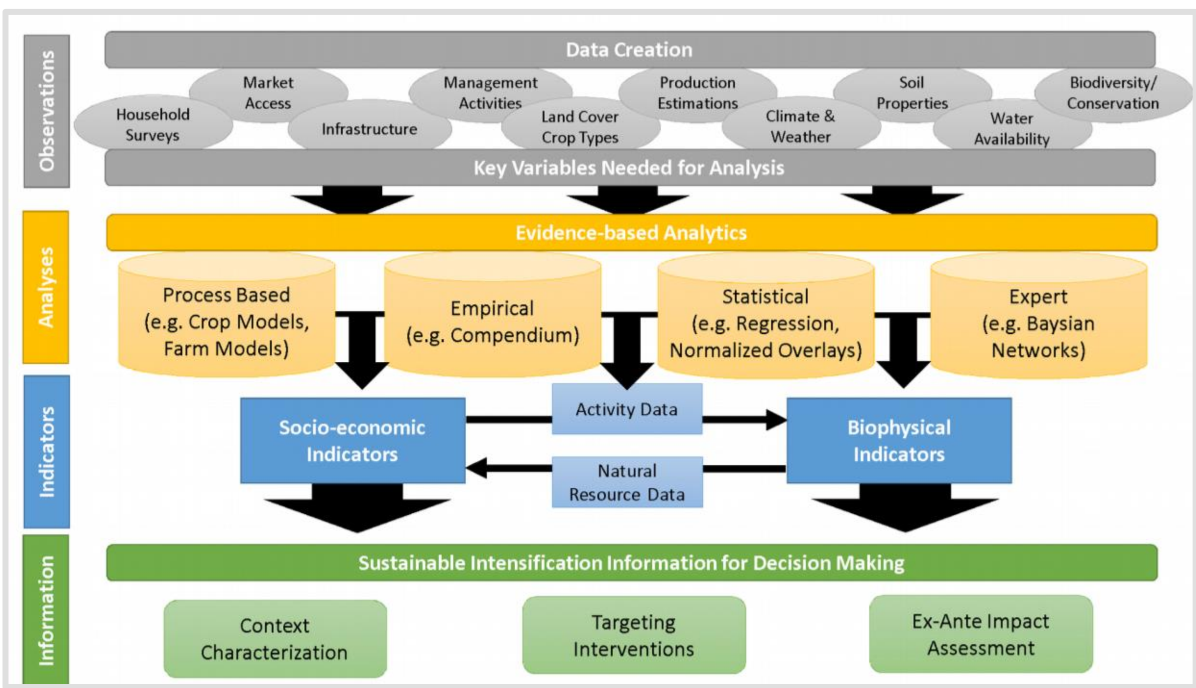


Maize yield potential (Yp; 103 kg ha^{-1}) simulated with the WOFOST model and predictions based on 856 training sites (black points on the map) via eight methods. MBIO, metamodel with bioclimatic variables; GWHT, weather generator; WINT, interpolation of daily weather data; IXYCLM, Interpolation with geographical and environmental covariables; GIWTH, weather generator with interpolated climate data; IXY, interpolation with location data only; MCLM, metamodel with climate averages; INN, nearest-neighbor interpolation.

We predicted Yp at the testing sites by using five main methods (eight methods if one considers within method variants): (i) weather interpolation followed by simulation; (ii) nearest-neighbor interpolation; (iii) thin-plate spline interpolation, either with or without covariates; (iv) Random Forest-based metamodels with either climatic or bioclimatic variables; and (v) weather generation from either climate data or interpolated climate data, followed by simulation. The metamodel with bioclimatic variables performed best (average root mean square error (RMSE) = 667 ± 111 kg ha^{-1}), followed by weather generation from climate data, weather interpolation, and spatial interpolation of yield with climatic covariables. The most commonly used method, nearest-neighbor interpolation, performed worst (RMSE = 1763 ± 472 kg ha^{-1}). We recommend that the optimal method for a particular study will depend on the simulation model, the region, weather station density, and other variables. Based on these activities, we also recommend that for estimating Yp, alternatives to nearest-neighbor interpolation should be considered.

Project 6: Spatial Targeting Agricultural Sustainable Intensification Investments: Linking Household Surveys with Spatial Data in Africa

This project was implemented by the International Center for Tropical Agriculture (CIAT), in close collaboration with the International Livestock Research Institute (ILRI) and Wageningen University (WUR). The goal of the project was to support the targeting of agricultural sustainable intensification investments by identifying where there is an urgent need in combination with high attractiveness and potential success of sustainable intensification. It aimed to map the current gradient of agricultural intensification and sustainability of this intensification in Tanzania as well as conditions that could support investments in agricultural sustainable intensification. It collated a wide variety of geo-referenced household-level data. Data points from very contrasting systems were included and thus allowed for a robust analysis of the on-the-ground conditions for intensification and sustainability. This data was used for mapping simple sustainable intensification indicators, from both the socio-economic and bio-physical domains. Also, a wide range of secondary spatial data was obtained, including indicators along the five different dimensions/domains of sustainable intensification as described in Musumba and Palm, 2016. A conceptual framework was developed, describing how best to relate household-level information on intensification and sustainability to the available spatial data. Some preliminary analysis was carried out within the project, while the methods, data, and tools will also be made available to end-users so that they can carry out their analysis.



Draft conceptual framework of the intensification

Project 7: Spatial profitability of alternative production strategies in maize-based smallholder farming systems in sub-Saharan Africa

This project was implemented by CIMMYT. Under this project, we have developed a flexible set of spatially-explicit analytical approaches for ex-ante evaluation of the feasibility and attractiveness of different agricultural technologies. The approach we use is based on the use of georeferenced yield response data (either from agronomic trials or farm survey data) to calibrate geographical yield models. Yield models are then linked to geographically explicit data on model parameters (e.g. soils databases) as well as mapped estimates of input and output prices. We are then able to compute the expected profits associated with a particular input usage at a particular location. Adding in stochastic components to the model (through seasonal rainfall), we may also address the riskiness of expected returns.

We have implemented different versions of this framework using the R programming language, which is in the process of being codified for sharing publicly (via an electronic handbook for agronomy at scale, supported by an aligned project). A peer-reviewed analysis that demonstrates the application of this framework is in progress. As a byproduct of this work, we also developed a set of methods for predicting input and output prices across space. This price modeling component is the basis of one paper under review and a chapter in the above-mentioned handbook.

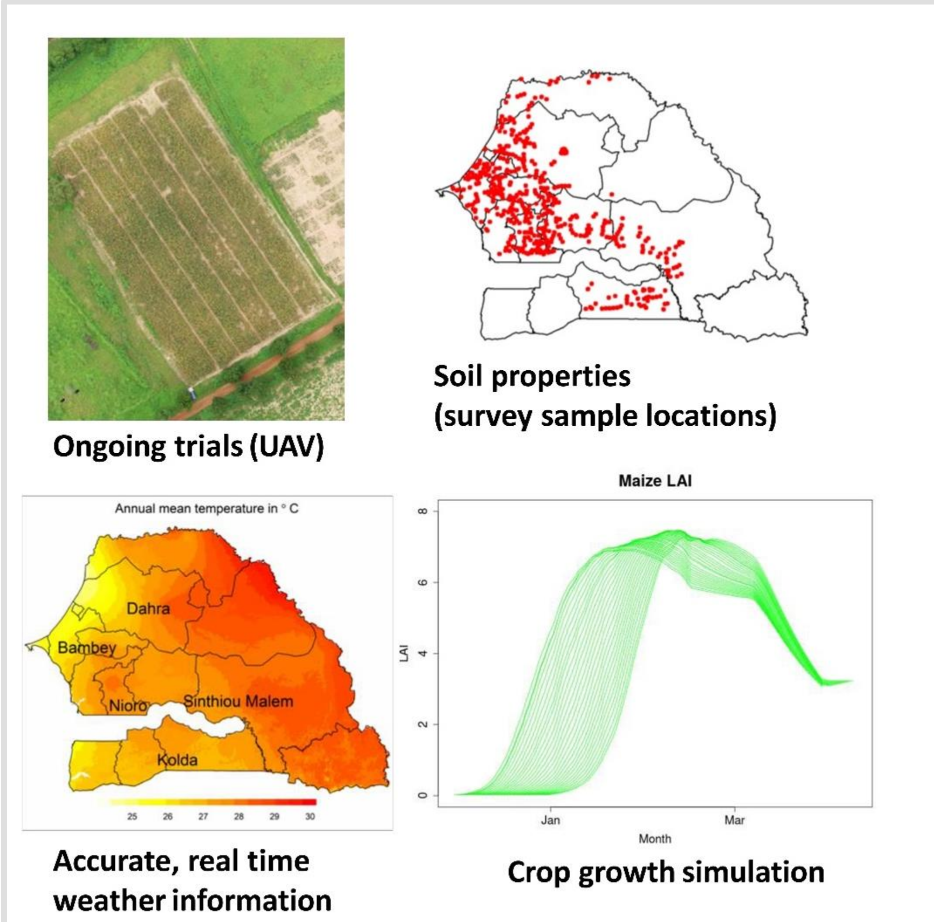
The framework is fundamentally flexible. For example, a variety of yield models may be used, e.g. production functions, structural models such as QUEFTS, machine-learning predictors. Similarly, there are a variety of ways in which uncertainty may be introduced. We anticipate the continued development of these ideas in subsequent projects.

Project 8: Improve resource use efficiency in crop production

In this multi-collaborator project, we are addressing several key components of the farming systems to improve resource use efficiency and productivity of the cropping systems. With Senegal as a pilot country, we focused on the following main activities:

- Conduct on-farm trials across the rainfall gradients to better understand the crop response to fertilizer
- Develop crop simulation models to improve our understanding of intercropping systems
- Create high-quality information on weather, soil properties and fertilizer access to capture the local variations
- Design location and crop-specific farmer advisory services combining the above learnings

The project was implemented by two key centers of the Institut Sénégalais de Recherches Agricoles (ISRA), Centre National de Recherches Agronomiques (CNRA) and Laboratoire National de Recherche sur les Productions Végétales (LNRPV). Collaborative agencies included Kansas State University, Regional Centre for Plant Drought Adaptation Study (CERAAS), Laboratoire National d'Etudes et de Recherches Vétérinaires (LNERV), Laboratoire Mixte International sur l'Intensification Écologique des Sols en Afrique de l'Ouest / Institut de Recherche et de Développement (UMR Eco&Sols/IRD), Unité de recherche Agroécologie et Intensification Durable des cultures Annuelles/ Centre de coopération internationale en recherche agronomique pour le développement (UR AIDA/CIRAD) and Crop Nutrition Laboratory Services Ltd (CROPNUTS).



Conceptual framework to combine different approaches to achieve resource efficiency

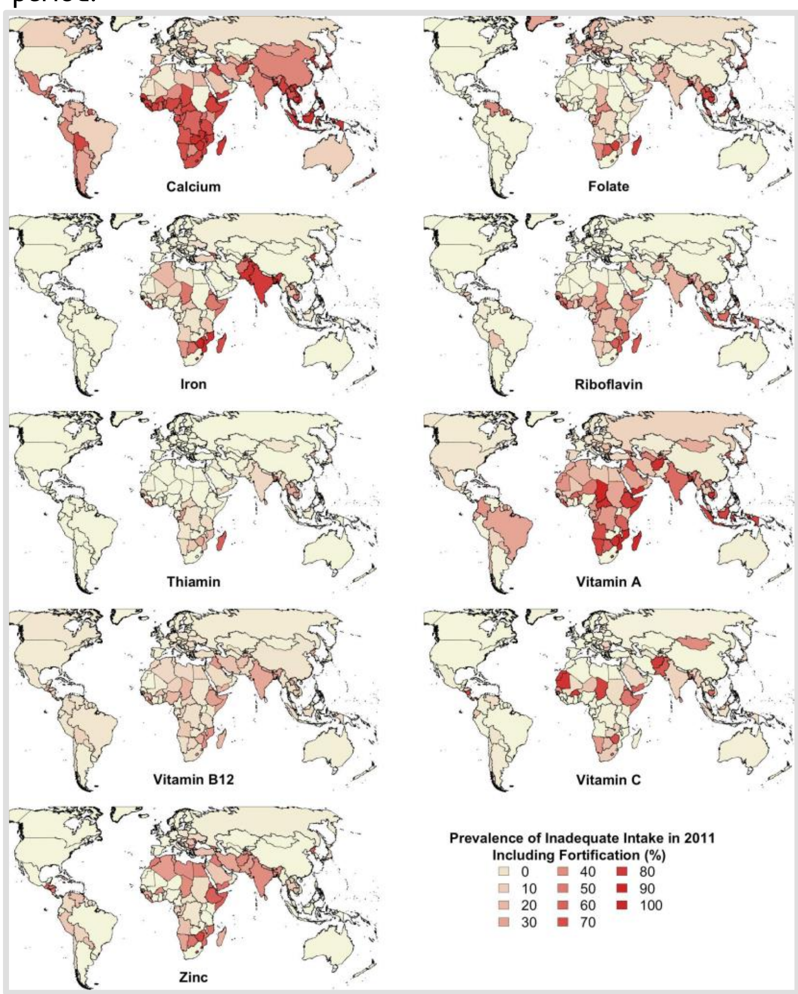
We have conducted 24 organic and mineral fertilizer treatments since the rainy season 2017 in 5 agro-ecological zones of Senegal (Dahra Djiloff, Bambey, Nioro, Sinthiou Malem, and Kolda) using four millet varieties (Souna 3, Thialack 2, IBV8004 and Sanio). Primary findings indicated that the fertilizer recommendation developed by ISRA in the 1970s is still applied without taking in to account the variability of soil and climate. These recommendations are not suitable for increasing millet yield and intensifying the production. We also completed a fertilizer price survey across Senegal using Kobotoolbox based questionnaire to better understand the fertilizer availability and quality survey across Senegal. We completed the nationwide soil survey in Senegal. Twenty-five hundred soil samples were collected across 1000 locations in Senegal. Two thousand samples have been analyzed by the Cropnuts Ltd in Nairobi. An additional 500 samples are being analyzed by AgroCares, Netherlands. This a unique accomplishment among the Feed the Future Innovation Lab supported projects. These projects also helped to improve weather data availability in Senegal. We have set-up six weather stations Senegal across multiple climatic zones. The weather data is continuously updated in the GFC weather data dashboard. We also introduced modern tools for agricultural monitoring applications. The project technician monitored crop trials/plots using the unmanned aerial systems (UAS) equipped with a multi-spectral camera.

We supported multiple (10+) MSc thesis from different universities in Senegal. Also, a number (5+) of Ph.D. candidates are engaged in ongoing research with weather data and soil moisture information in five research stations across Senegal. This initiative also produced the first-ever licensed UAS operator in Senegal.

Objective 2: Relation Between SI And Nutrition, Socio-Economic And Environmental Outcomes

Project 1: Global trends in diets

This project was implemented by the University of California Davis, in close collaboration with the Harvard T.H. Chan School of Public Health. Understanding dietary patterns are vital to reducing the number of people experiencing hunger (about 795 million), micronutrient deficiencies (2 billion), and overweight or obesity (2.1 billion). We characterize global trends in dietary quality by estimating micronutrient density of the food supply, the prevalence of inadequate intake of 14 micronutrients, and the average prevalence of inadequate intake of these micronutrients for all countries between 1961 and 2011. Over 50 years, the estimated prevalence of inadequate intake of micronutrients has declined in all regions due to the increased total production of food and/or micronutrient density. This decline has been particularly strong in East and Southeast Asia and weaker in South Asia and sub-Saharan Africa. Sub-Saharan Africa is the only region where dietary micronutrient density has declined over this 50-year period.

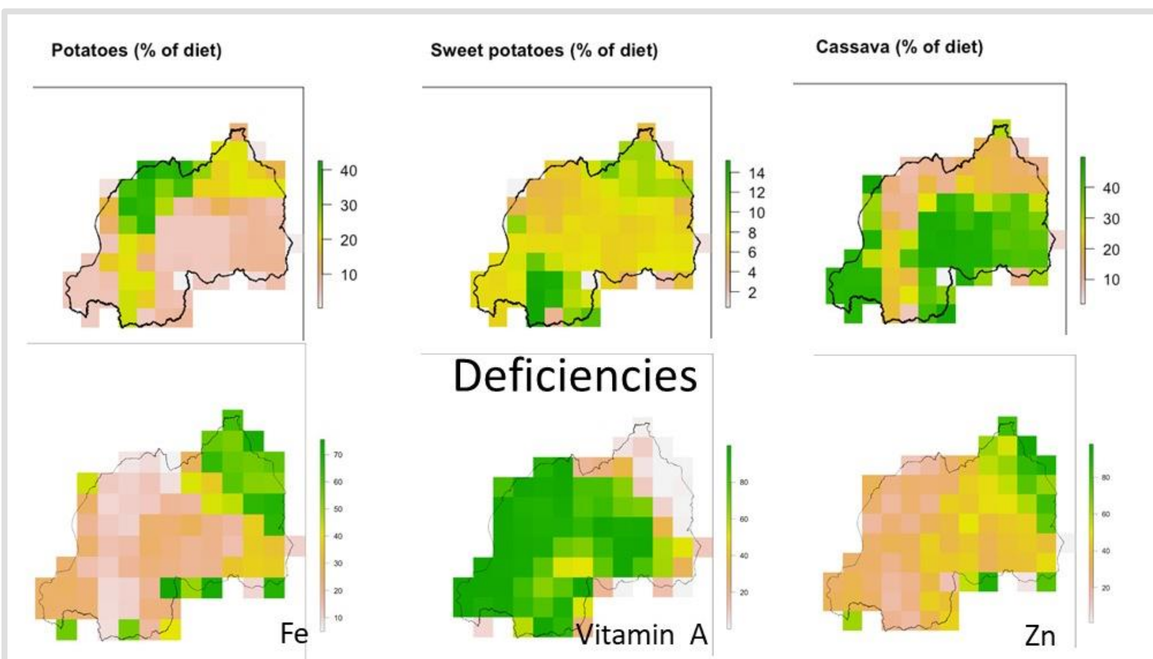


The country-level estimated prevalence of inadequate intake of nine micronutrients in 2011, including the contribution of fortification

At the global level, micronutrients with the lowest levels of adequate estimated intake are calcium, iron, vitamin A, and zinc, but there are strong differences between countries and regions. Fortification has reduced the estimated prevalence of inadequate micronutrient intakes in all low-income regions, except South Asia. The food supply in many countries is still far below energy requirements, which suggests a need to increase the availability and accessibility of nutritious foods. Countries, where the food energy supply is adequate, show a very large variation in dietary quality, and in many of these countries, people would benefit from more diverse diets with a greater proportion of micronutrient-dense foods. Dietary quality can be improved through fortification, biofortification, and agricultural diversification, as well as efforts to improve access to and use of micronutrient-dense foods and nutritional knowledge. Reducing poverty and increasing education, especially of women, are integral to sustainably address malnutrition.

Project 2: Fine-scale prediction of local diets

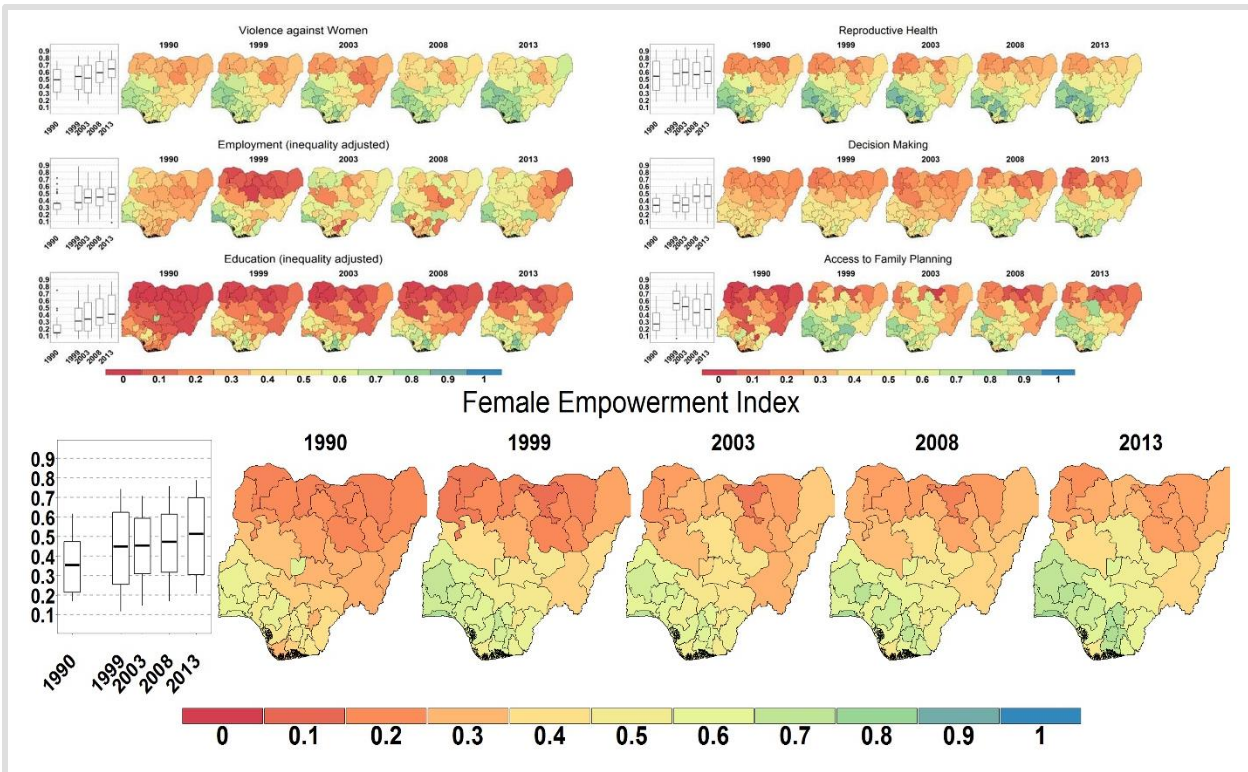
This project is implemented by the University of California Davis. While national-level dietary trends are important to understand the global conditions, it is extremely important to quantify the regional variations in local diets to design intervention strategies. In this ongoing project, we created a spatial database of local diet from various secondary sources at fine spatial resolution. Multiple data sources have been utilized to estimate the prevalence of inadequate intake of 14 micronutrients for all countries. An R-package is under development to downscale the national level estimates of local diets. Some preliminary outcome of the project is shown below with Rwanda as a pilot country.



Spatially modeled food production and nutrient deficiency at a local scale

Project 3: Understanding female empowerment

This project was implemented by the University of California Davis. Female empowerment continues to be an important human-rights and development goal. However, existing approaches to quantify empowerment have been criticized for their limited scope and reliance on country-level indicators which potentially obscure important subnational variation. We developed the Female Empowerment Index (FEMI), which uses spatially explicit data from Demographic and Health Surveys (DHS) to track multiple domains of women's empowerment at a subnational level. The index is based on six categories of female empowerment: education, decision making, physical and sexual violence, reproductive health, employment, and contraception. To illustrate its use, we computed the FEMI for the 36 states of Nigeria, using questions asked to 98,542 women between 15 and 49 years old from five DHS surveys between the years of 1990 and 2013. The FEMI has a potential range between zero (low empowerment) and one (high empowerment) and is calculated as the mean proportion of positive outcomes in the six categories for women. Between 1990 and 2013, the index revealed that Nigerian women experienced greater overall empowerment, rising from a score of 0.34 to 0.48. However, there was substantial subnational variation in the trajectory of index and subcategory scores, corresponding to lower gains in the north compared to the south. Most individual categories showed steady improvement during this period, except for contraception, which peaked in 1999 but declined thereafter and has not fully recovered since. The FEMI can be readily computed for other countries, and its ability to track spatial and temporal variation in woman's empowerment across a broad set of categories may make it more useful than existing approaches.



Subnational variations in FEMI sub-categories and overall FEMI scores

Project 4: Map historical land-use changes associated with agricultural expansion in Cambodia

This project was implemented by the Royal University of Agriculture (RUA), in close collaboration with the ILRI, and GFC members. To understand the historical land use land cover change (LULCC) dynamics in Cambodia, this study used remote sensing image analysis and qualitative research methods to explore the major drivers. We concentrated our activities in four provinces: Battambang, Pursat, Siam Reap, and Kampong Thom. First, we applied the Rural Household Multi-Indicator Survey (RHOMIS) integrated with participatory GIS for gathering in-situ information in which the questionnaire is built on the ODK platform. The form that is built for the ODK platform is divided into two different forms: RHOMIS form for household and field plot survey form. The household survey form is mainly created for characterizing livelihood and the asset while the field plot survey form will be used for ground-truthing and gathering related information. Second, we are exploring remote sensing methods for classifying satellite images such as Sentinel (1A, 1B, and 2A) and Landsat

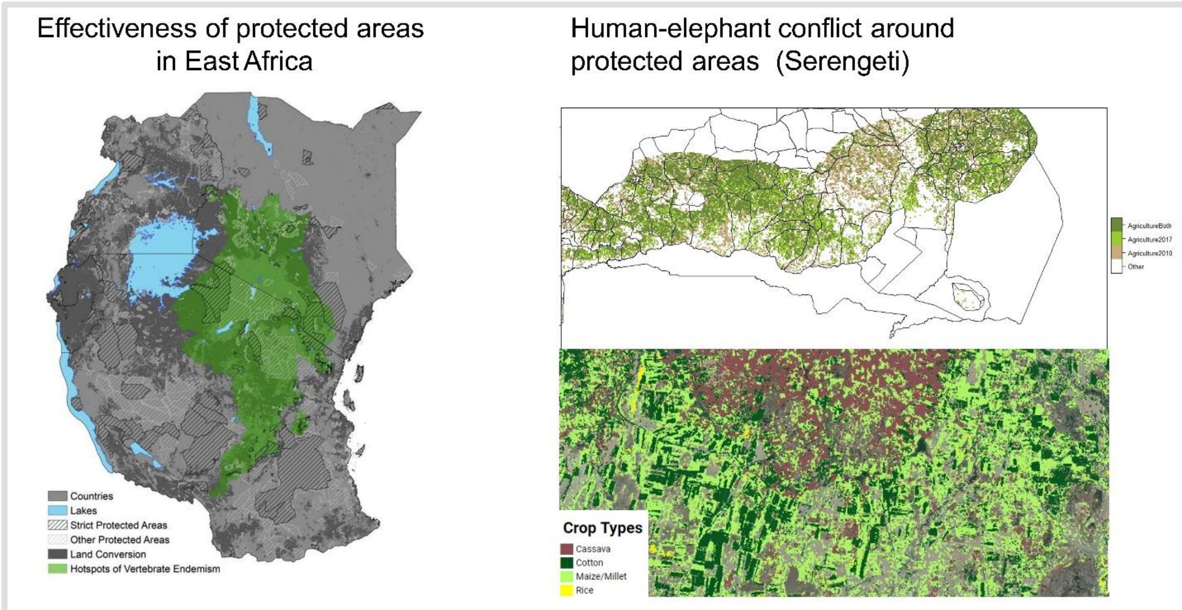
(TM5, ETM+, and LC8) using free and open sources software. The rich and diverse dataset collected under this project is currently being analyzed.

Based on the project activities, we received a grant from the USAID PEER grant titled "Establishing cropland database in Cambodia from remote sensing satellite data". We also secured additional funding from ACIAR for a project titled "Land suitability assessment and site-specific soil management for Cambodian upland". To scale-up the project activities and strengthen research collaboration with other USAID supported projects, we provided technical support to CE SAIN to install five weather stations in the technology parks. We also collected aerial photos for supporting the ASMC project. In nutshell, the project team continuously provided support for modern data collection (e.g., GPS, small drones and other ICT-based (near-) real-time rapid survey instruments) to other partners working in Cambodia.

(a) UAV data collection (b) Survey data collection (c) Remote Sensing based rice map

Project 5: Sustainable intensification and conservation challenges

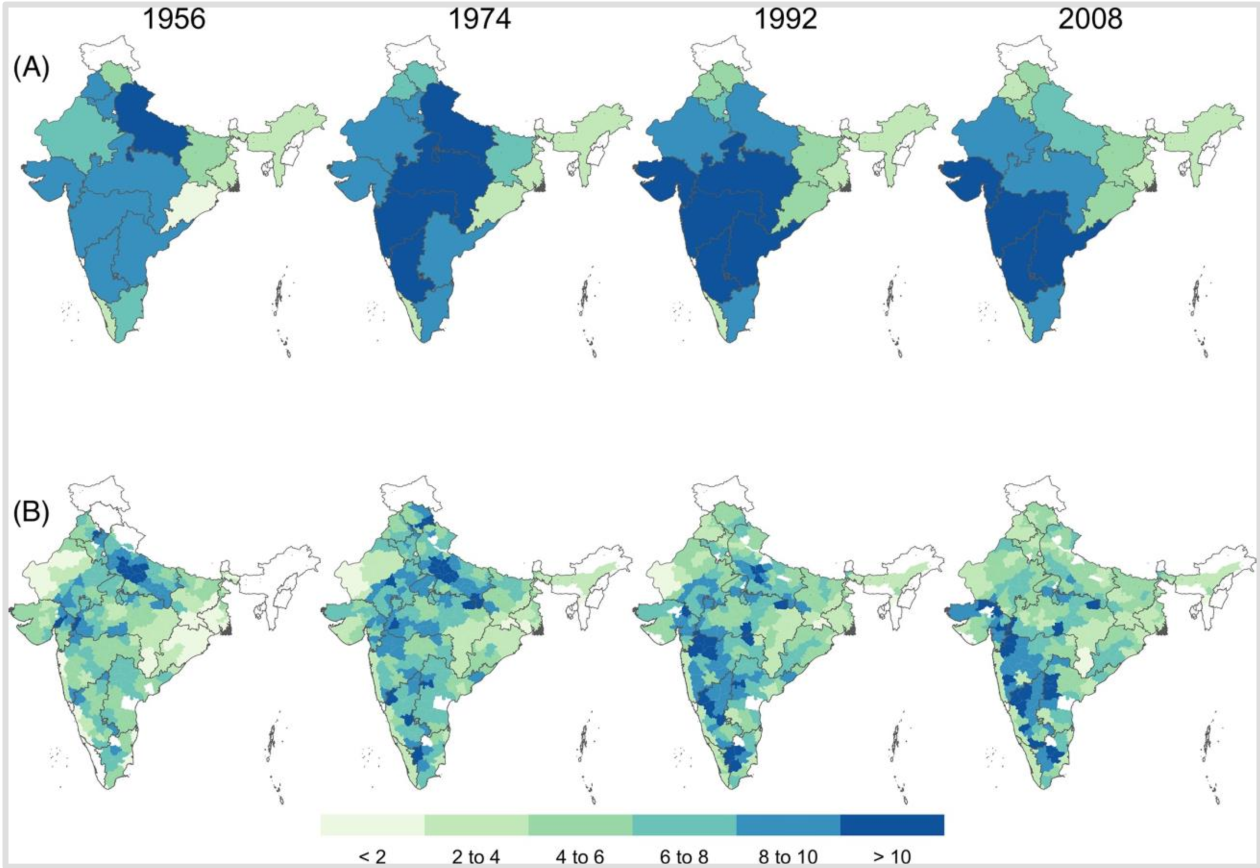
In these projects, a group of UC Davis researchers explored how effective the protected areas (PA) are under the agriculture extensification. In the first study, we assessed how the PAs have been encroached upon by agriculture and other land use. We find that East African protected areas cover 86% of ecoregions well (>10% threshold of ecoregion representativeness set by the Convention on Biological Diversity's Aichi Target 11), some very well (>90% - Rwenzori-Virunga montane moorlands and East African montane moorlands). In contrast, Masai xeric grasslands and shrublands, Somali Acacia Commiphora bushlands and thickets, and Southern Swahili coastal forests and woodlands are poorly represented. Protected areas cover at least 10% of the distribution of 256 of 303 East African endemic and near-endemic terrestrial vertebrate species (the latter defined here as having 90% or more of their range in East Africa). However, 37% of these species' ranges do not have at least 10% coverage by strict PAs and only 26% of endemic species have at least half of their range covered by PAs. Encouragingly, we find that only 6.8% of East African protected areas have been converted to agriculture or other human use since gazettement. Only 1.6% of strictly protected areas have been converted providing very strong evidence that strict protection is the most enduring way of safeguarding habitat.



Another study in Tanzania focused on the Ikorongo and Grumeti Game Reserves (IGGR) and Ikona Wildlife Management Area and in the communities surrounding the reserves. These protected areas form an important buffer between Serengeti National Park and communities and maintain habitat critical to the seasonal migration of wildebeest, zebra, and gazelle through the Greater Serengeti-Mara Ecosystem. The impacts of human-wildlife conflict, specifically elephant crop-raiding, are significant in this area. We quantified agricultural land cover change and grassland conversion to *Acacia drepanolobium* due to grazing pressure around reserves in Tanzania from 1984 to the present. Using ground-truthed land cover points around IGGR, we identified agricultural expansion over the past 30 years. We employ Landsat time-series data through Google Earth Engine, a cloud-based platform, to classify pixels for the base year (2017), comparing different classification techniques at various scales. In contrast to previous work, which showed little agricultural expansion close to reserves, we found that agriculture within a 10km buffer around the reserve increased from 5% in 1984 to 22% in 2017. Grassland conversion increased as well, particularly in areas with concentrated cattle grazing. We are trying to understand if specific cropping practices increase the risk of human-wildlife conflicts and how this information can be used to maintain the balance between agricultural activity and wildlife movement.

Project 6: Agricultural intensification and crop diversification

With India as a case study, we attempted to improve our knowledge of historical variation in Spatio-temporal variation of agro-biodiversity. We used time series of national (1947–2014) and district-level (1956–2008) crop distribution data for India to show that despite strong agricultural intensification after 1960, the average crop species diversity at the district level was stable, but increased at the country-level. While there was a decline in diversity in the major rice and wheat-producing regions of northwestern India, associated with intensification of the production of these crops, diversity in western and southern India increased due to the expansion of oilseeds and horticultural crops that replaced millet and sorghum.



Crop diversity in India for in 1956, 1974, 1992 and 2008 at the (A) district and (B) state level. Data was not available for some districts and small states (white areas) for certain years. Diversity is expressed as the "effective number of species".

These opposite, but related, trends in crop-level diversity at the sub-national level partially canceled each other out at the national level, but there nevertheless was a noticeable increase in overall crop diversity in India during this period. Our results illustrate how patterns of change in crop diversity need to be considered at different levels of aggregation, and how a decrease in diversity associated with intensification and specialization in one area, may be associated with increased diversity elsewhere, and that support for intensive agriculture with relatively low crop diversity in some regions may be associated with an increase in crop diversity in other regions and at a higher level of aggregation. This framework is being extended to other countries where adequate spatial-temporal information on crop production is available.

Objective 3: Develop Open Data And Tools For Agricultural Development

Project 1: Improved high resolution interpolated gridded climate surface for global land areas: WorldClim 2

This project was implemented by the University of California Davis. We created a new dataset of spatially interpolated monthly climate data for global land areas at a very high spatial resolution (approximately 1 km2). We included monthly temperature (minimum, maximum and average), precipitation, solar radiation, vapor pressure, and wind speed, aggregated across a target temporal range of 1970–2000, using data from between 9000 and 60 000 weather stations. Weather station data were interpolated using thin-plate splines with covariates including elevation, distance to the coast and three satellite-derived covariates: maximum and minimum land surface temperature as well as cloud cover, obtained with the MODIS satellite platform. Interpolation was done for 23 regions of varying size depending on station density. Satellite data improved prediction accuracy for temperature variables 5–15% (0.07–0.17 ∘C), particularly for areas with a low station density, although prediction error remained high in such regions for all climate variables. Contributions of satellite covariates were mostly negligible for the other variables, although their importance varied by region. In contrast to the common approach to use a single model formulation for the entire world, we constructed the final product by selecting the best performing model for each region and variable. Global cross-validation correlations were ≥ 0.99 for temperature and humidity, 0.86 for precipitation and 0.76 for wind speed. The fact that most of our climate surface estimates were only marginally improved by the use of satellite covariates highlights the importance of having a dense, high-quality network of climate station data.

WorldClim Version2

WorldClim version 2 has average monthly climate data for minimum, mean, and maximum temperature and for precipitation for 1970-2000.

You can download the variables for different spatial resolutions, from 30 seconds (~1 km^2) to 10 minutes (~340 km^2). Each download is a "zip" file containing 12 GeoTiff (.tif) files, one for each month of the year (January is 1; December is 12).

variable	10 minutes	5 minutes	2.5 minutes	30 seconds
minimum temperature (°C)	tmin 10m	tmin 5m	tmin 2.5m	tmin 30s
maximum temperature (°C)	tmax 10m	tmax 5m	tmax 2.5m	tmax 30s
average temperature (°C)	tavg 10m	tavg 5m	tavg 2.5m	tavg 30s
precipitation (mm)	prec 10m	prec 5m	prec 2.5m	prec 30s
solar radiation (kJ m^{-2} day^{-1})	srad 10m	srad 5m	srad 2.5m	srad 30s
wind speed (m s^{-1})	wind 10m	wind 5m	wind 2.5m	wind 30s
water vapor pressure (kPa)	vapr 10m	vapr 5m	vapr 2.5m	vapr 30s

Below you can download the standard (19) WorldClim Bioclimatic variables for WorldClim version 2. They are the average for the years 1970-2000. Each download is a "zip" file containing 19 GeoTiff (.tif) files, one for each month of the variables.

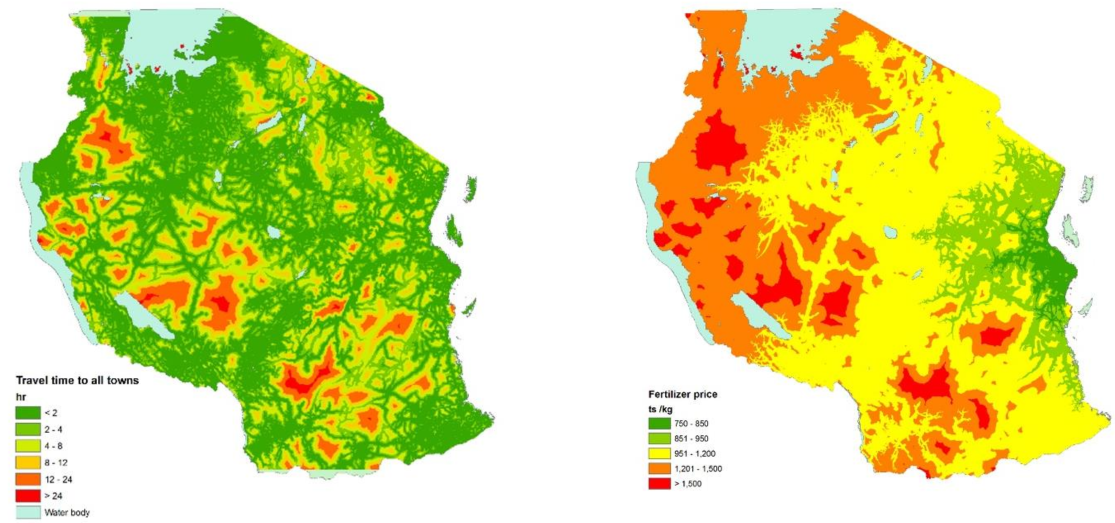
variable	10 minutes	5 minutes	2.5 minutes	30 seconds
Bioclimatic variables	bio 10m	bio 5m	bio 2.5m	bio 30s

Variables are available at http://worldclim.org/version2.

WorldClim2 data products have been made publicly available at different spatial resolutions, from 30 seconds (~1 km2) to 10 minutes (~340 km2). Standard (19) WorldClim Bioclimatic variables for WorldClim2 has been generated. In the future, WorldClim2 will have significantly a greater number of bioclimatic variables than version 1. We are currently generating a time series of interpolated climate surfaces. SIIL country-specific data set is available from the GFC data website http://gfc.ucdavis.edu/data/ as well as in the GFC/SILL dataverse https://dataverse.harvard.edu/dataverse/GFC.

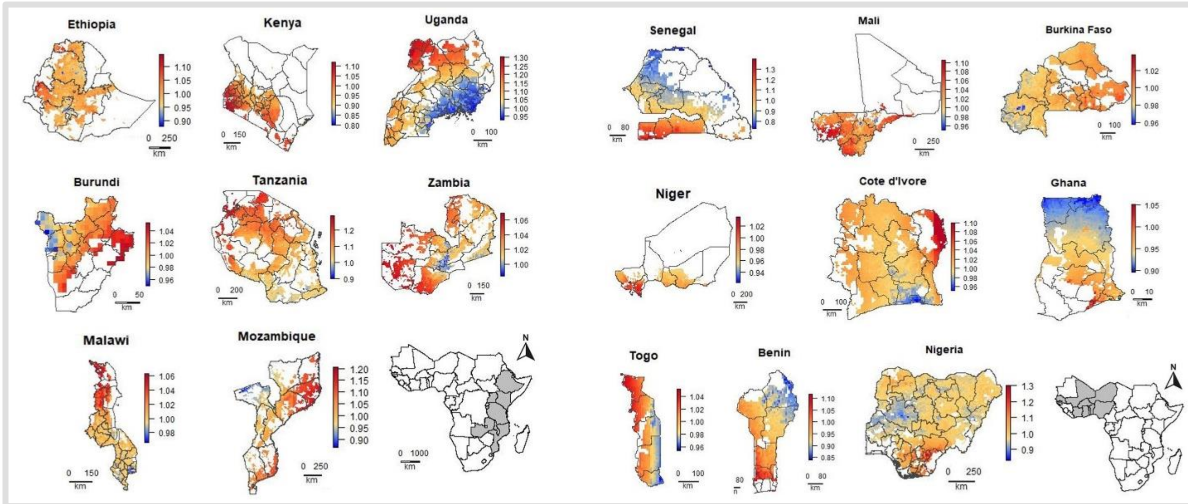
Project 2: Improved modeling framework for spatial accessibility and transportation cost for an improved spatial price modeling

This project was implemented by the International Food Policy Research Institute (IFPRI). For Tanzania as a pilot country, we developed a novel analysis framework to incorporate Google Distance Matrix as an additional source of model parameters and evaluation data for on-road routing. This unique approach showed the potential of providing more reliable travel time estimates for both on-road and off-road areas. Using this new framework, we developed an updated spatial data layer of fertilizer prices for Tanzania. Farm-gate fertilizer price data were pooled from various surveys and used to develop a new price model. Finally, we provide recommendations to further develop this analysis in the future and expand to other countries.



(a) Updated accessibility to all cities (b) Modeled fertilizer price surface

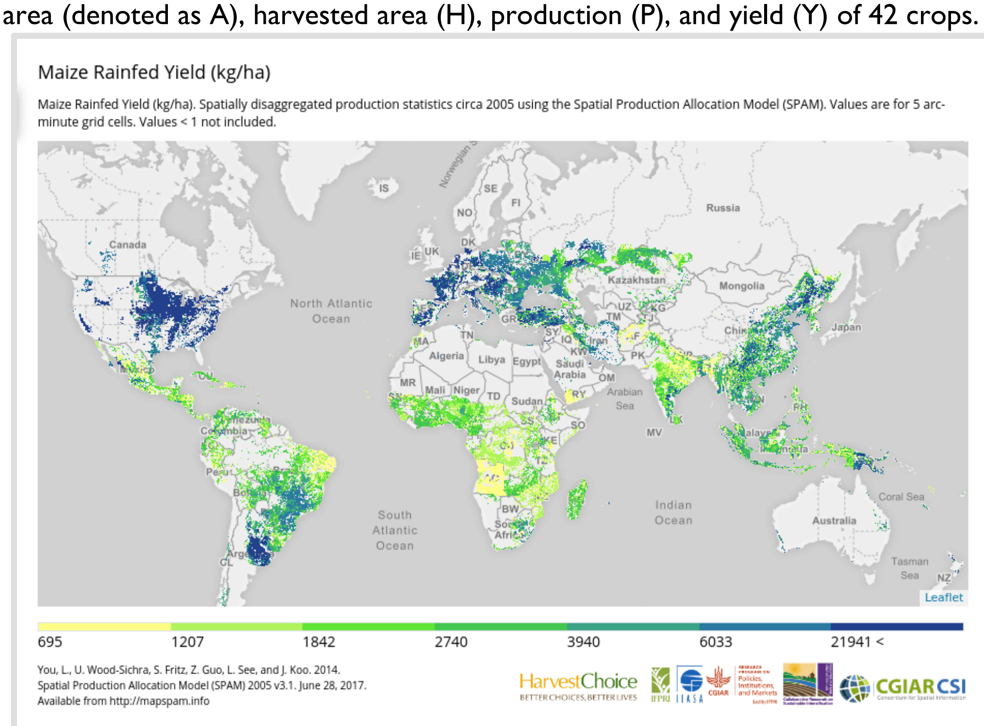
In a recent work done by UC Davis, CIMMYT and IFPRI, the fertilizer price modeling framework was extended to better understand patterns of, and opportunities for, fertilizer use, location-specific fertilizer price data may be relevant. We compiled local market price data for urea fertilizer, a source of inorganic nitrogen, in 1729 locations in eighteen countries in two regions (West and East Africa) from 2010–2018 to understand patterns in the spatial variation in fertilizer prices. The average national price was lowest in Ghana (0.80 USD kg^{-1}), Kenya (0.97 USD kg^{-1}), and Nigeria (0.99 USD kg^{-1}). Urea was the most expensive in three landlocked countries (Burundi: 1.51, Uganda: 1.49, and Burkina Faso: 1.49 USD kg^{-1}). Our study uncovers considerable spatial variation in fertilizer prices within African countries. We show that in many countries this variation can be predicted for unsampled locations by fitting models of prices as a function of longitude, latitude, and additional predictor variables that capture aspects of market access, demand and environmental conditions. Predicted within-country urea price variation (as a fraction of the median price) was particularly high in Kenya (0.77–1.12), Nigeria (0.83–1.34), Senegal (0.73–1.40), Tanzania (0.90–1.29) and Uganda (0.93–1.30), but much lower in Burkina Faso (0.96–1.04), Burundi (0.95–1.05), and Togo (0.94–1.05). The work indicates new opportunities for incorporating spatial variation in prices into efforts to understand the profitability of agricultural technologies across rural areas in Sub-Saharan Africa.



Predicted relative urea price of urea (local price divided by the observed median national price) for areas with cropland in eight East and nine West African countries.

Project 3: Mapping crop production statistics

This project was implemented by the International Food Policy Research Institute (IFPRI). This activity produced the first beta version of IFPRI's Spatial Production Allocation Model for 2010 (SPAM 2010). Much of the efforts were concentrated on the collection of sub-national crop production statistics for the four focus countries of the Sustainable Intensification Innovation Lab: Burkina Faso, Ethiopia, Senegal, and Tanzania. Underlying data was collected by mining reputable websites, such as the official websites of Bureau of Statistics or Ministry of Agriculture in focus countries, or leveraging personal connections to IFPRI staffs or close partners at relevant institutions, combined with the collection of any information relevant to crop-wise irrigation in those countries, followed by thorough checking for addressing issues on data quality and missing data. Each of the output files includes four types of data: physical area (denoted as A), harvested area (H), production (P), and yield (Y) of 42 crops.



Project 4: Developing an open infrastructure for mapping crop distribution and estimating crop yield to support index insurance projects

This project is implemented by UC Davis members, in collaboration with the Feed the Future Innovation Lab for Markets, Risk and Resilience. Many remote sensing-based methods have been developed to estimate crop productivity but to date, there has been very little systematic comparison of what approach works best, or which approaches work best under certain conditions (in particular regions) or for certain purposes. To address the lack of comparison and generalization we are developing (i) a database of field data from different regions to train models; (ii) new software that implements several methods and supports standard workflows in R; and (iii) a set of capacity-building materials. This is an ongoing project and the progress can be tracked at https://gfc.ucdavis.edu/events/agrin/html/. The current implementation focuses on Kenya, Tanzania, and Ghana.

Project 5: Towards standardization of farm household surveys

This project was implemented by the International Livestock Research Institute (ILRI). Targeting interventions and monitoring progress are, arguably, two of the greatest and least addressed challenges in scaling up interventions that aim to address smallholder poverty, inequity, and food security through sustainable intensification. To supply essential harmonized data on the functioning and welfare of smallholder livelihoods to support this targeting and monitoring we developed the Rural Household Multiple Indicator Survey (RHoMIS in short). We successfully scaled out this survey approach together with a wide range of partners, resulting in a database of more than 24000 farm households across 31 low- and middle-income countries. These analyses helped different organizations in the evaluation of the livelihood interventions they were implementing, and we have embedded the RHoMIS approach in other assessment and evaluation frameworks.

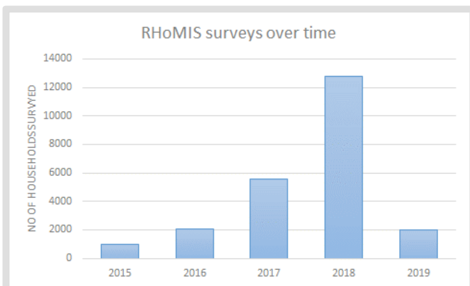
The original setup of the RHoMIS system happened in 2015. The system encompasses not only the survey instrument itself, but is a complete framework in which the survey definition, the data server, the R indicator quantification and visualization code, and the reporting setup communicate seamlessly. Over the last two years, this system has been streamlined and further developed.

Another focus area was communication and outreach. During the project period, we have set up a new website (www.rhomis.org), which includes basic information about our work, the key instruments we use and shows the results of our work. We also now have a monthly blog post where we explain our recent work and make it more accessible. The website has been a huge success and now on average has around 40 views per day (which amounts to more than 14000 views per year).

Besides the further development of the RHoMIS tool itself (with regular version updates where we fine-tune the instrument), we have, in collaboration with the IITA team of Rwanda, developed a mini-RHoMIS that maps completely to the full RHoMIS, but only needs 15-20 minutes per household. We are currently testing this version in Burundi and DRC. With this 'mini-RHoMIS' we are also exploring collaboration with the Big Data Platform of the CGIAR, and then more specifically with the ontology activity within the Socio-Economic Data community of practice.

> Developing a systematic data ontology for the mini-RHoMIS would be a powerful step to further improve the data interoperability between our RHoMIS results (to which, as said before, the mini-RHoMIS maps seamlessly) and other data sources within the CIGAR.

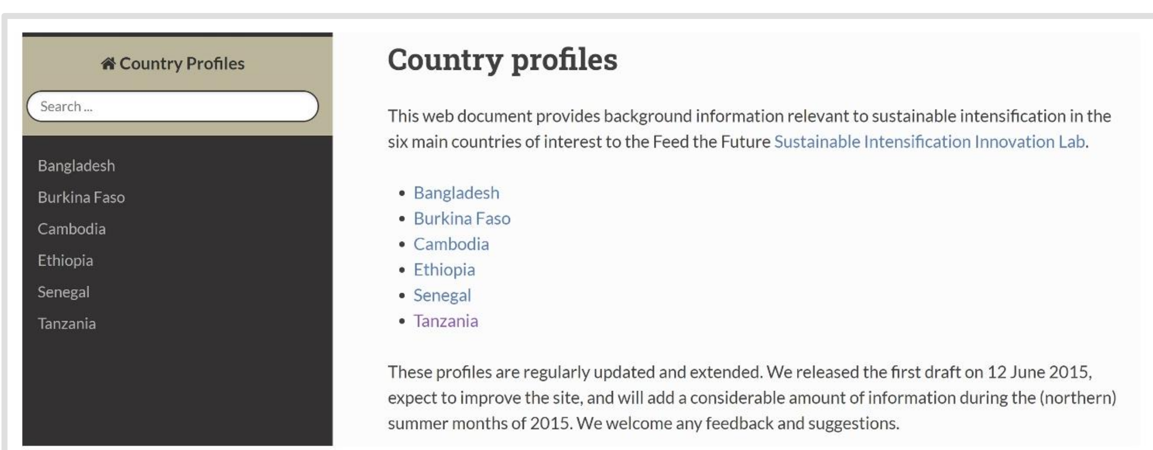
A last key activity we worked in the last year is to make an integrated link between our RHoMIS results and a mapping of our results on the Sustainable Intensification Assessment Framework (SIAF), a framework developed by Michigan State University and Columbia University, funded by USAID Feed the Future SIIL. SIAF was developed to assess five the sustainability of agricultural interventions integrally and uses indicators across domains (productivity, economic, social, human and environment) to do that. By including a few extra indicators into the RHoMIS system (mainly focusing on the environment, traditionally the weakest part of the RHoMIS system) we were able to get a balanced quantification of the SIAF assessment. This RHoMIS-SIAF setup was applied within the AfricaRISING Ethiopia project within a survey in which 800 households were interviewed in four contrasting regions in Ethiopia. Detailed analyses of the survey results are now underway, and two manuscripts are planned/drafted.



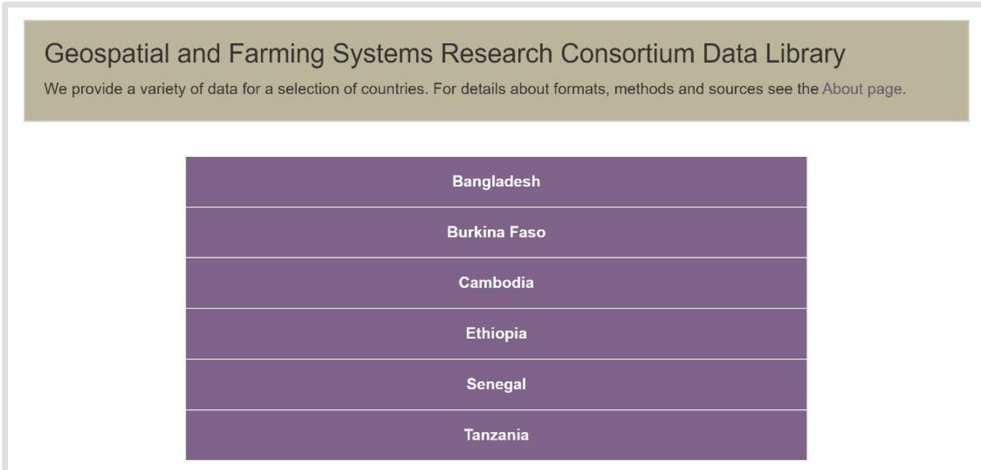
Project 6: GFC country profile and data portal

We maintained consortium websites with interoperable data, open-source software, reproducible case studies, and other materials to allow others to engage in similar types of research. We developed country profiles for the GFC focus countries (http://gfc.ucdavis.edu/profiles/) and continuously updated them. Through this project, we have set a positive example to promote and support the use of open data in agriculture, particularly in developing countries.

We built a weather data dashboard for distributing data from the SIIL network of weather stations in Burkina Faso (2), Cambodia (5) and Senegal (6). The website is available here: https://weather.gfc.ucdavis.edu/. We expect this website to remain active for future years, as long the stations continue to upload the data. We regularly contributed to SIIL data management plans for different cases. In many cases, we are the first team to test different data submission platforms introduced by the SIIL management team. Currently, we account for more than one-third of the data submitted to the SIIL-dataverse.



http://gfc.ucdavis.edu/profiles

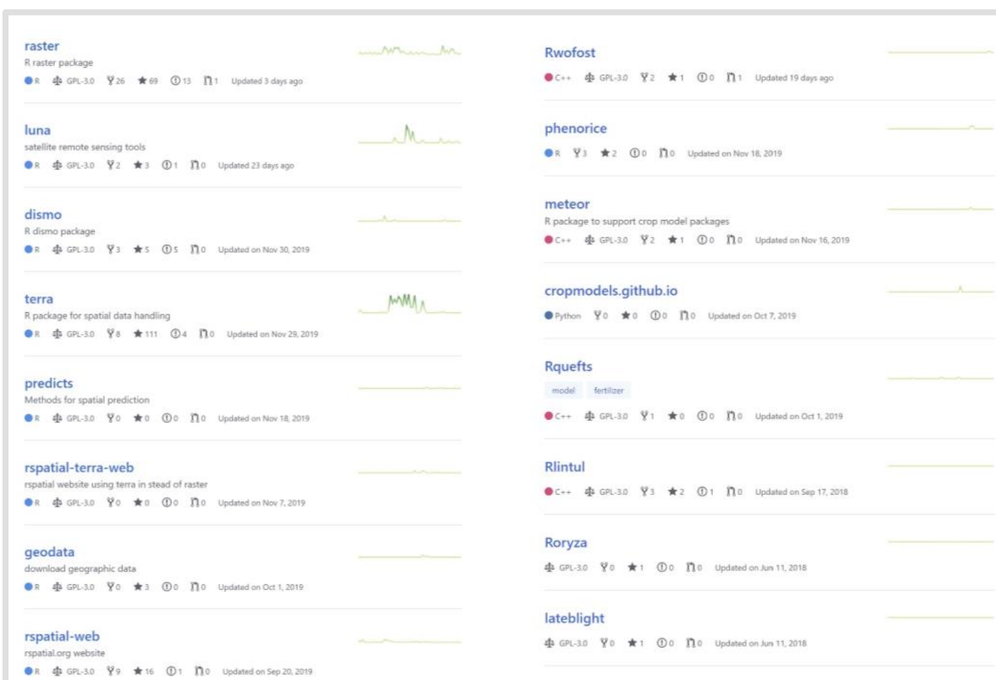


https://gfc.ucdavis.edu/data/

Project 7: R-packages for spatial data modeling, access, and crop simulation models
We made significant progress in developing open-source R-packages. Altogether we released more than 15 R-packages for spatial data and crop growth modeling. We also developed user-friendly tools to ingest and process data from high-resolution Planet data and processing UAV data. All these packages will be actively maintained by the UC Davis team and other community members. Details about the packages can be found in:

- Spatial data access and handling packages: https://github.com/rspatial
- Crop growth simulation packages: https://github.com/cropmodels

Package development activities are shown below:



Project 8: Introduce unmanned aerial systems (UAS) and weather stations for data collection

We provided unique support to our in-country colleagues by providing cutting-edge as well as necessary data collection platforms to support agricultural research. We supported the installation and maintenance of five weather stations in Cambodia and six in Senegal. These stations provide useful information on temperature, wind, humidity and solar radiation sensors and soil moisture, and equipped with a weather station with cell (GSM) data uplink for automatic data upload. Currently, we have an archive of weather station data for around 2 years. We also installed soil moisture sensors. We also supplied two stations in Burkina Faso and three stations in Tanzania that our project partners could not install in time due to several reasons. We developed data management plans with SIIL and concerned in-country partners for the data distribution.

We organized training events on small Unmanned Aerial Systems (sUAS) based remote sensing data collection and processing in Cambodia and Senegal. In-country partners in these two countries have a complete kit, sUAS with Regular Color and Multispectral cameras, for near-surface remote sensing data collection. They used the instruments to collect images of the experimental plots (or study locations) at frequent intervals during the growing seasons. UAS equipment in Cambodia was also being used to monitor an experimental plot managed by ASMC. We also continued to develop and optimize UAV data collection and processing systems at UC Davis with researchers from different disciplines. We created a website for UAV flight planning and post-flight data collection. More details available at:

- UAS flight operation: https://gfc.ucdavis.edu/guides/flightops/index.html
- UAS data processing: https://gfc.ucdavis.edu/guides/qgis_lab.html

UAV training and weather station installations in Senegal and Cambodia

Objective 4: Organize Workshop/Courses And Prepare Web-Based Material On Spatial Data Analysis For Agricultural Development

We were committed to organize regional training workshops/courses and prepare online course material on spatial data analysis for agricultural development and promote and supporting the use of open data within SIIL and the larger agricultural development community. We conducted several traditional in-country training courses for project collaborators and others but released materials that are also suitable as standalone distance learning. In the last five years, we trained 200+ participants in 10+ short (1-5 days) training events. We also supported 70+ bachelors, masters, Ph.D. and postdoctoral researchers in the long-term training activities. Our primary training material website https://rspatial.org is live and being continuously updated to provide more content for the most relevant topics. It is visited by hundreds of researchers around the world every month.

Tanzania, 2016 Senegal, 2017 Cambodia, 2018

Some of our training workshops are mentioned below:

1. Tanzania, August 2016. Spatial Data Analysis and Modeling for Agricultural Development, with R (45+ participants). Website: https://gfc.ucdavis.edu/events/wk-tza-aug16.html

2. Ethiopia, May 2017. Geo-wiki web tool for crop boundary digitization (10+ participants).

3. Senegal, October 2017. Senegal UAS and mobile data collection training (20+ participants). Website: https://blogs.k-state.edu/siil/2018/07/03/senegal-uas-training-october-2017/

4. Cambodia, February 2018. Cambodia UAS and mobile data collection training (15+ participants). Website: https://blogs.k-state.edu/siil/2018/11/07/cambodia-uas-training-february-2018/

5. Tanzania, August 2018. Spatial data handling with R. (70+ participants). We also organized a sub-theme for the conference on 'Open spatial data and software for Sustainable Intensification of Agriculture in Africa' which included more than 25 presentations on the following broad topics: i) free and open-source software and data for agricultural development, ii) FOSS4G tools for natural resource and livestock resource management, understanding spatial variation in market access and prices, and soil and nutrient management, iii) Remote sensing applications in agriculture. Website: https://foss4g4ag2018.sched.com/

6. Cambodia, December 2018. Spatial Data Analysis and Modeling in R for Agricultural Development (15+ participants).

7. Utilization of Research Outputs

We designed our research projects to achieve the greatest impact. Most of our work is conducted in collaboration with in-country partners (private-sector, international NGOs and other stakeholders). Therefore, the knowledge generated in this project should be helpful for both public and private sector users. While the ultimate beneficiaries of these tools are smallholder farmers in developing countries, we see several core constituencies who will directly benefit from these tools:

- Scientists and policy analysts in national agricultural research systems, universities, policy analysis units in government, and other institutions
- Scientists and analysts working within the international agricultural research systems, e.g. the CGIAR and UN systems
- Students in graduate programs studying applied computer science for agronomy and development applications
- Our work has proven its relevance for a series of international NGOs (TreeAID, OneAcre Fund, Global Diversity Foundation, SNV) who were willing to collaborate and to get our support in their applications.
- Specific tools like RHoMIS is an efficient, ready-made solution for these partners and could lift the baselining and M&E approaches of these projects to a higher level. Besides this applied side of using RHoMIS, we have also been able to generate a series of scientific outputs based on the data, and we are only just starting to harvest the benefits of the overall harmonized database.
- Satellite remote sensing-based tools can reduce the cost of the program-level impact assessments, as well as the cost of the crop-insurance policies. Both their program evaluation and insurance are based on conducting hundreds of individual crop cuts in farmers' fields from both participating and control group farmers. Satellite-based yield estimates could substantially reduce the cost of obtaining accurate yield estimates, even if some crop cuts are still needed for calibration.

Short term training on flying drone DJI M100, using Xenmuse X3 and Parrot Sequioa Camera (Testing fly in FLMLA garden). Photo credit: Robert Hijmans.

Open-access data and rigorous analysis for peer-review publications ensure the quality and reliability of our research output. Another important part of our work is dedicated outreach through stakeholder engagement and large-scale events both in the U.S. and in host countries, as well as a robust program of ongoing news media outreach, web publications and other content tailored for the broader development community. The result of these efforts includes a wealth of accessible and adaptable knowledge, toolkits for scaling interventions and a wide network of stakeholders working to promote greater opportunities for small-scale agricultural households.

8. Future Challenges and Opportunities

All GFC supported research projects showed promising progress and a lot of useful ideas emerged on how to bring them together during several stakeholder meetings. However, due to the limited time allocation of each of the scientists in the project team, still, a lot remains to be done to achieve the actual potential. Data storage and distribution will be a major challenge as not all the projects will have continued support or research teams to maintain the activities. Technologies like UAV and weather stations not only provide us reliable cost-effective information but also boost local capacity building. It is critical to have trained research staff for maintaining equipment and supporting research projects beyond the SIIL project duration.

We have multiple continuing projects supported by different funding agencies, including USAID grants. A couple of projects in Cambodia supported by USAID PEER program are developed based on GFC supported activities. Our projects using remote sensing indicate great promise for using new satellite datasets to map smallholder agriculture in Eastern Africa. A project in East Africa on quality assurance of index insurance programs is now conducted in collaboration with the Feed the Future Innovation Lab for Markets, Risk and Resilience. Additional funding through CGIAR has allowed us to expand our efforts in the field of agricultural data science.

In the beginning, the potential of geospatial tools is not obvious for researchers from different domains. However, after several stakeholder meetings, we are presented with numerous collaboration opportunities. Due to resource and time constraints, we were not able to support all such requests. It was interesting to see that most of these requests are related to assessing scaling-up potential for specific adoption strategies or technologies. Moving forward, we would like to focus on the following topics:

- Assess the potential of SIIL innovations ("Scale-up")
- Agricultural data science web site
- Develop case studies on sustainable intensification using the data created by SIIL community
- Provide easy access to data (e.g. soil, climate, and weather) to 'non'-spatial researchers
- Implement farmer, extension, and policy facing applications

We, therefore, recommend a continued investment to realize the full potential of applying geospatial tools and data to sustainable intensification of agriculture.

9. Publications

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11. Hammond J., Pagella T., Fraval S., Wichern J., Teufel N., Kihoro E., Herrero M., Rosenstock T.S., van Wijk M.T. The rapid pace of change for rural smallholders in East Africa: prosperity is driven by off-farm income, in tandem with agricultural intensification. Submitted to PNAS.
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10. Datasets Produced

Due to the nature of the consortium's research using global data (e.g. remote sensing, climate records) and spatial modeling, the projects are not often tied to any focus regions (e.g. village). Therefore, the locations are not mentioned explicitly as all the datasets are spatial and contain geographic information.

- WorldClim: https://www.worldclim.org/
- GFC Data Portal: https://gfc.ucdavis.edu/data/

- Harvard Dataverse: We have submitted 24 datasets and 850+ files in the GFC dataverse (includes published, restricted and unpublished data, see below).

Details available at https://dataverse.harvard.edu/dataverse/GFC (SIIL users need to log-in to see the complete list of data).

Status of dataverse data submission by the GFC researchers

CONSORTIUM 2

appropriate scale mechanization

Consortium 2

Appropriate Scale Mechanization

1. **Lead Institution:** University of Illinois at Urbana-Champaign (UIUC)
    - U.S. Collaborating Institution:
        - Michigan State University (MSU)
        - Kansas State University (KSU)
        - North Carolina A&T State University (NCA&T)
        - Texas A&M University
    - International Collaborating Institutions
        - **(ask about this list and the collab. Organizations page on the website)**

2. **Research Team:**
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    - Co-Investigator:
        - Dr. Prasanta Kalita (UIUC)
        - Dr. Kuan Chong Ting (UIUC)
        - Dr. Alex Winter-Nelson (UIUC)
        - Maria Jones (UIUC)
        - Dr. Ajit Srivastava (MSU)
        - Dr. Tim Harrigan (MSU)
        - Dr. Nanda Joshi (MSU)
        - Dr. Manuel Reyes (KSU)
        - Dr. Carlos Campabadal (KSU)
        - Dr. Ben Schwab (KSU)
        - Dr. Paula Faulkner (NCA&T)
        - Dr. Niroj Aryal (NCA&T)

3. Executive Summary

The Appropriate Scale Mechanization Consortium (ASMC) has facilitated appropriate-scale agricultural mechanization for sustainable intensification in four developing countries: Bangladesh, Cambodia, Ethiopia, and Burkina Faso, concentrating on technologies that increase labor productivity and timeliness while enabling sustainable cropping systems, reducing drudgery especially for women and targeting value chain development with private sector involvement for scaling.

> The ASMC has adopted a user-centric systems approach implemented in each country via established Innovation Hubs and Field Hubs with attention paid to the whole value chain and focused on stakeholder engagement, tertiary and outreach capacity building, and a strong emphasis on enhancing the participation of women in technology adoption.

Different technologies have been explored, developed, manufactured, and promoted to the point of them being scaled up via sustainable business models through private sector-public sector engagement. In each of the countries, at least four technologies have been earmarked for scaling. An example is mini-combine harvesters for rice in Bangladesh that have been shown to reduce harvest losses by 5% with a labor-saving of 65%. Importation and deployment of this technology have been facilitated by engagement with private sector companies. From a policy standpoint, the Bangladesh government announced very recently that it would provide a 60% subsidy for this combine harvester to promote its use by smallholder farmers in the country. Promotion of conservation agricultural practices is a key topic in each country and technologies have been identified that elevate such practices and contribute to improved soil health. In the case of vegetable production, the introduction of hand tools that reduce drudgery especially for women has been an important outcome. Leveraging more efficient solar-powered water-lifting devices has opened up opportunities for more efficient irrigation systems impacting vegetable and forage production.

Gender engagement has been a significant focus in the project and has been addressed through various activities. These have included gender sensitization training for understanding gender roles for technology adoption conducted in each country with Innovation Hub members and stakeholders; and development, refinement, and application of a gender technology assessment tool accommodating technologies at various scales of development, including prototypes. Considerable opportunities exist for continuing the work initiated by the ASMC. These include preparing and applying a Technology Readiness Assessment of each of the technologies identified for potential scaling and transformational change; continuing efforts to engage with the private sector to facilitate the technology scaling process; pursuing a tertiary capacity building effort to create a B.S. curriculum combining technology and business; expanding on existing gender and youth engagement efforts.

4. Project Partners

- University of Illinois at Urbana-Champaign
- Michigan State University
- Kansas State University
- North Carolina A&T State University

Target Country Partners

Bangladesh
Bangladesh Agricultural University
ADM Institute for the Prevention of Postharvest Loss
Feed the Future Innovation Lab for the Reduction of Postharvest Loss

Cambodia
Ministry of Agriculture, Forestry, and Fisheries of Cambodia
CIRAD
Horticulture Innovation Lab
Conservation Agriculture Service Center - Ministry of Agriculture, Forestry and Fisheries

Ethiopia
Bahir Dar Institute of Technology, Bahir Dar University
Feed the Future Innovation Lab for the Reduction of Postharvest Loss
Innovation Lab for Small Scale Irrigation
Tillers International

Burkina_Faso
Bobo-Dioulasso Polytechnic University
Tillers International

5. Project Goals and Objectives Goal:

Overall Goal

To assess/develop/adapt/implement/promote appropriate-scale agricultural mechanization for sustainable intensification focusing on smallholder farming systems in Feed the Future countries associated with targeted geographical regions and enhance the participation and experience of women in the adaptation/adoption of technologies for agricultural development.

Overall Objectives

Objective 1: Assess challenges and opportunities and recommend appropriate forms for agricultural mechanization

Objective 2: Identify entities and projects engaged in mechanization research in the target countries to establish collaboration

Objective 3: Implement gender-sensitive, scale-appropriate mechanization strategies in coordination with USAID mission goals and objectives of the Sustainable Intensification Innovation Lab

Objective 4: Enhance women's skills and education in using machinery, equipment, and tools, and addressing agricultural issues

Objective 5: Measure and evaluate the impact of appropriate scale mechanization strategies on sustainable intensification

6. Overview of Activities

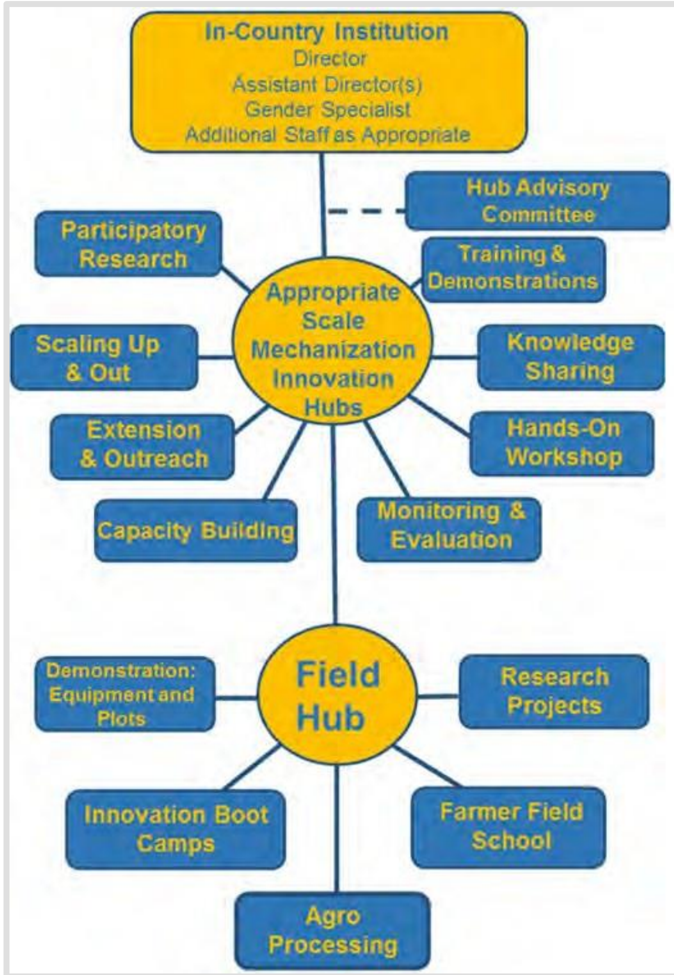
Overall Approach

The key concept of ASMC was to create an ecosystem of innovation such that in-country institutions would be empowered to seek mechanization solutions to improve intensification sustainably. To this effect, the ASMC emphasized the following:

- Promoting a user-centric process of engagement with local stakeholders via the establishment of in-country Innovation Hubs and Field Hubs (see Figure below).
- Identifying and establishing technologies and machinery that are versatile, affordable, scalable, and reduce the drudgery of operations performed by women
- Pursuing and facilitating activities that build in-country capacity, integrate gender considerations, create measurable outcomes and impacts, provide important knowledge to relevant stakeholders, and facilitate the creation of business ventures for scalable technologies
- Ensuring that a systems approach is followed to account for, integrate, and evaluate economic, environmental and social impacts.

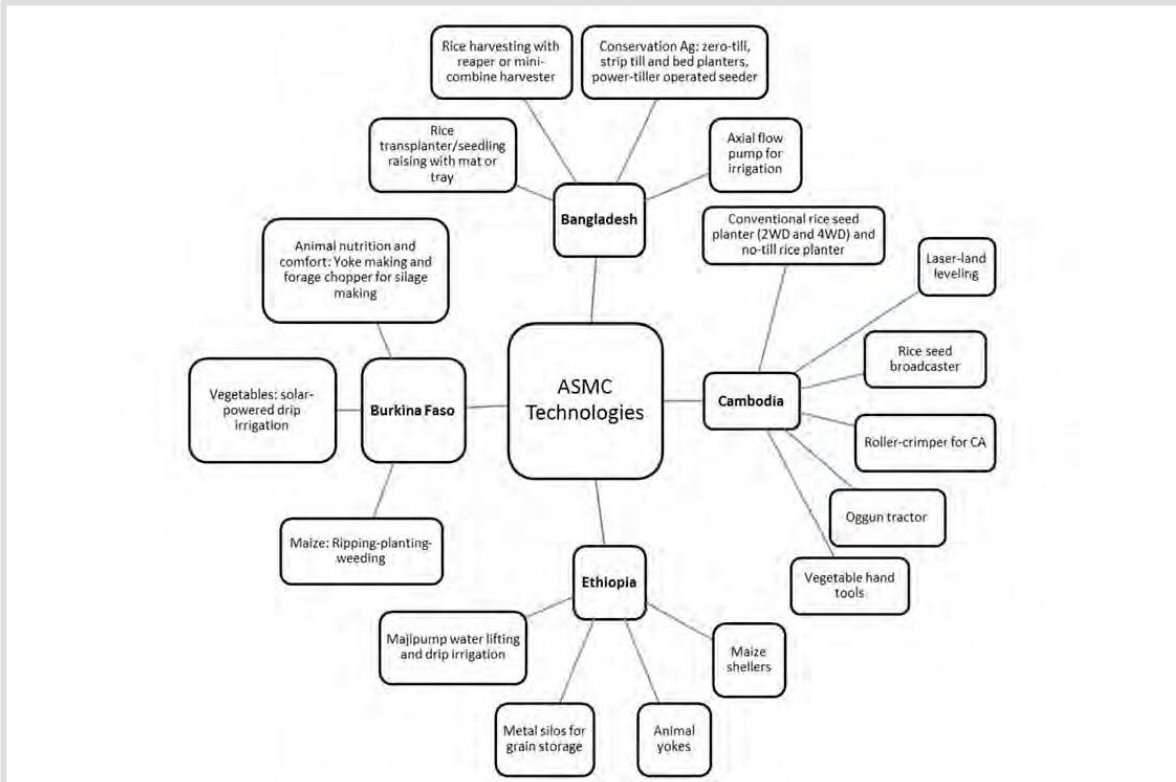
The mechanism for launching the hub in each country was the completion of a pre-launch survey by the host institution followed by a visit to the country by the ASMC team with a two-day workshop including a broad range of participants representing key stakeholders in the region with particular emphasis on smallholder farmers and women. At each workshop, the stakeholders were responsible for identifying key challenges and opportunities in the context of appropriate scale mechanization and the relevant value chains. Also, they identified the top priorities and tasks to be addressed by the ASMC. Further development in each country was the establishment of field hubs located typically in the rural area and providing a mechanism for connecting more closely with the farming community.

During the four years of the project, a total of three meetings were held with the Science Committee appointed to provide expert input related to the activities of ASMC.



Technology Development and Assessment

In each of the four countries, processes of assessing/developing/adapting/implementing/promoting technologies for sustainable intensification of agricultural production systems have taken place, accounting for specific value chains in each country. The specific technologies that have come to the forefront for further evaluation and scaling are illustrated in the figure below. Some of the technologies are expected to be regionally relevant and hence be potentially useable in neighboring countries, subject to local conditions. Some commonality can be expected for Bangladesh and Cambodia, and Ethiopia and Burkina Faso, given similarities in value chains.



Gender Engagement And Technology Assessments

Gender-sensitive mechanization attributes/constraints were addressed initially in the launching workshops in each country and then followed up via the baseline survey results. Gender specialists from the US-based team helped coordinate activities with in-country appointed gender specialists. Focus Group discussions were held in each country as a means of identifying and seeking potential solutions to issues of gender inequality. Subsequently, ASMC worked with the Integrating Gender and Nutrition within Agricultural Extension Services (INGENAES) project to develop a one-year gender strategy from 2018 - 2019. The strategy focused on building the capacity of ASMC Innovation Hubs to integrate gender, and conduct Gender Technology Assessments of the technologies developed and promoted by ASMC.

Building Capacity Building of Innovation Hubs to Integrate Gender into Mechanization

To ensure successful agricultural mechanization, one needs to understand users: male and female farmers. Furthermore, one needs to understand the different roles men and women play to design better innovations. To generate understanding about the role of gender and its relevance to mechanization and technology adoption, ASMC conducted a one-day introductory gender training in the four consortia countries.

Globally 142 people were trained including ASMC Innovation Hub staff, PIs, professors, research scientists, faculty, students (university and technical training centers), and public sector representatives. The training utilized participatory methods and adult learning principles. In-country gender specialists led certain activities and helped foster discussion in the local language. Example activities included role-playing gender roles within a rural household to understand men and women's time and labor constraints, and investigating intra-household power dynamics and its influence on the adoption of technologies.

Building upon the initial training, ASMC trained multidisciplinary teams (53 participants in total) that included engineering faculty, students and staff on gender frameworks and the gender technology assessment methodology. These multidisciplinary teams implemented the assessment in select project intervention areas by conducting qualitative interviews with female and male farmers, service providers and extension officers.

The training conducted focused on building the capacity of in-country gender specialists through training, toosl, and skills. The training also purposefully integrated youth through university students from different discipkines to understand key concepts and learn to conduct research.

Burkina Faso trip to train staff of gender basics and conduct technology assessments on the gender sensitivity of the planter technology. Photo credit: Maria Jones.

Innovative Approaches to Including Gender within Agricultural Mechanization

Globally, women represent on average 43% of the agricultural labor force in developing countries. Although mechanization can help reduce time, labor and drudgery of agricultural production and improve quality of life, female farmers face multiple barriers in adopting mechanization. Barriers to adoption range from technology design to access to credit, land, and information to purchase, access or use the technology. Furthermore, women face intra-household barriers and, in many countries, negative socio-cultural perceptions associated with women using agricultural machinery. While closing the gender gap in women's access to agricultural technology is considered a key strategy for rural women's economic empowerment, there is a real challenge in determining how a program can better include women in agricultural mechanization from the get-go.

ASMC attempted to tackle this challenge through the development of a 'lean' gender technology assessment. Adapted from the INGENAES Technology Assessment toolkit and the Gender Toolkit for Small Scale Irrigation Technologies, the assessment incorporates principles of Human-Centered Design to identify practical recommendations that can be easily and quickly incorporated into program activities. Six early-stage technologies promoted by ASMC in Burkina Faso, Cambodia, Bangladesh, and Ethiopia were assessed for gendered barriers and enablers at various stages of technology uptake: design (user's needs), dissemination (learning), adoption (access) and continued use (intra-household dynamics). Simple approaches were then identified to reach, benefit or empower women through the technologies.

Findings and Resulting Action Steps

Below are three examples of innovative approaches to including gender in agricultural mechanization:

Fee-for-service arrangements have made the mechanization needed to implement Conservation Agriculture (CA) more accessible to smallholder farmers who no longer need to purchase capital-intensive machinery. In Cambodia, ASMC worked with different stakeholders to promote the adoption of CA by building the CA service provision business. However, in the project intervention area, women were traditionally not engaged in farm production decisions, which affected their participation in CA training. Through the assessment, it was identified that, although less visible, women are playing an important role in the household's adoption of mechanization technology. Women were household financial managers who paid for technologies, contracted and negotiated with service providers, and paid service providers. This challenged the assumption that CA adoption was solely a field management decision controlled by men. A solution that stemmed from the assessment was to target women with tailored CA training that meets women's practical needs and strategic interests. This includes tailored content (financial reasons to adopt CA), accessible training (time, location, catering for low literacy), financial resources (access to credit) and a resource list of service providers.

Similarly, in Bangladesh, conservative socio-cultural norms restrict women's ability to participate in paid work outside the home, including field-based agricultural work. Women operating machines is also considered socially unacceptable. The assessment helped identify two demographic groups of women who represented untapped potential in the mechanization market as clients needing service providers and as entrepreneurs. Women who face the double burden of managing the farm and household due to the out-migration of male members stand to benefit from service providers offering mechanized planting, transplanting, or harvesting services. Knowing about the technologies will benefit women and enable them to be better farm managers or joint managers.

Additionally, farmers who own machinery can benefit as rural entrepreneurs who offer machinery to farmers on an affordable fee-for-service basis, which leads us to the second demographic - female (and male) members of farmer associations. Farmer associations provide better access to markets, extension services, and opportunities for group ownership of a service provision business. An Integrated Pest Management club interviewed in Wazirpur successfully provided thresher, reaper, transplanter and mini-combine harvester services to over 70 farmers every season. The revenue was used to pay youth operators and mechanics, and profits were invested back into the club. Working with women's groups is an approach to ensure mechanization benefits women, even if they do not operate the machines themselves.

In Burkina Faso, farmer organizations play a critical role in enabling household technology adoption through the provision of training and credit, and in connecting farmers to markets. In particular, the Union des professionnels agricoles de l'Est et du Centre-Est (UPPA-Houet) has a mandate to reach women, with women forming 52 percent of its membership. Women members cited the Union as a key trusted source for information and training on new technologies. Although husbands are key decision-makers in a household's adoption of new technology, they were particularly keen to adopt technologies their wives promoted from training received at the Union. ASMC is using this information to promote a locally manufactured animal-drawn planter designed to lessen women's drudgery, time and labor during the planting season.

> The women also believed that it was important for them to introduce relevant innovations to their husbands: "If women bring this innovation and introduce it to the husband, then the husband will buy it and let them [women] do something else with their time."

Lessons learned in Phase 1 and Next Steps for Phase 2

Technologies are not inherently gender-neutral. Technology developers, scientists, and stakeholders need to do more to ensure that new technologies will reach and benefit both men and women farmers.

Programmatic lessons learned that can be applied to the next phase include developing a suite of evidence-based tools that can be adapted across different technologies and contexts. Additionally, there needs to be more research to understand how programs can reach, benefit, or empower women with technologies when women are not involved in field-level production activities, or there are strong social norms against women using or 'owning' technologies. This could be through the development of evidence-based approaches that work to reach, benefit and empower women to access and benefit from mechanization.

Inter-related, there is a gap in both capacity and knowledge sharing on gender and technologies across Innovation Labs.

Management lessons learned that need to be applied in the next phase include the critical need for Leadership buy-in to integrate gender across a project or Innovation Lab. This includes understanding amongst PIs and management entities on the importance to integrate gender into program activities. This also feeds into the need to hire gender specialists and provide them with a budget, direction, tools, and technical assistance to ensure gender integration across the consortia to enable gender integration at both the U.S. and in-country levels. There also needs to be a clear emphasis on hiring female faculty and students from technical disciplines such as engineering, economics, and agronomy.

7. Accomplishments & Utilization of Research Outputs (Country-Level)

Bangladesh

Status and need for agricultural mechanization in Bangladesh

Bangladesh is predominately an agricultural country and approximately 82% of the country's population lives in rural areas and most of them are making their living exclusively on agriculture. The total cropped area of the country is about 14.0 million ha with a cropping intensity of 180%. Paddy is the main staple crop of Bangladesh accounting for 76% of total cropped area and 95% of cereal production. At present, there are about 35,000 tractors, 5,50,000 power tillers, 32,912 deep tube wells, 14,24,136 shallow tube wells, 1,50,613 low lift pumps, 17,90,000 hand sprayers, 77,000 knapsack sprayers, 1,50,000 open-drum threshers, 2,20,000 closed drum threshers, 18,100 maize shellers, and about 25,81,761 different sizes of diesel engines operating in the agricultural sectors. These machines significantly improved tillage, irrigation, and threshing of paddy. However, two major rice production activities, transplanting and harvesting in the country remain manual all over the country. The present trend shows that there is about 45% labor shortage during peak transplanting and harvesting seasons causing delays in transplanting and harvesting causing a significant loss in crop production. High priority interventions are needed to promote the introduction of modern capital machinery and capacity building of local manufacturers in terms of technical, financial and market linkages. Additionally, the Southern Delta region of Bangladesh is lagging in the adoption of modern agricultural technologies due to its adverse agro-ecological characteristics due to salinity, waterlogging, inadequate control over water resources and repeated crop losses due to natural calamities.

> The adoption of appropriate-scale mechanization for sustainably using limited water resources for irrigation and conservation agricultural practices is ugently needed to increase crop production and economic emancipation of the region.

ASMC Goal for Bangladesh

The project identified machines for testing and adoption for mechanizing transplanting, harvesting, conservation agriculture (CA) and water management using axial flow pumps to increase the productivity of the existing cropping pattern, timeliness of operations, early establishment of the second crop, and increase yield. To promote mechanization and strengthen the agricultural machinery manufacturers in Bangladesh, several organizations have formed a strong partnership for the development and adoption of farm machinery in the country and capacity building. Under the leadership of Bangladesh Agricultural University (BAU), organizations such as Bangladesh Agricultural Research Institute (BARI), Bangladesh Rice Research Institute (BRRI), Rural Development Academy (RDA), Bangladesh Academy for Rural Development (BARD) and the Department of Agriculture Extension (DAE) have formed a Knowledge Hub for coordinating activities, knowledge sharing, and to provide training and innovation support aimed at sustainable intensification of agricultural mechanization in Bangladesh. The last three years of interventions indicate that there are visible changes in crop productivity and profitability from 5.6% to 19% and 27 to 52%, respectively.

Scientific advancement, accomplishment, and limitations of technology

Rice Transplanter

The technical performance of two available transplanters (riding-type and walking-behind type) was evaluated in puddled and dry paddy field conditions in the southern delta regions of Bangladesh. Since the riding-type transplanter (RT) is more expensive, the walk behind-type transplanter (WBT) is primarily selected for evaluation and adoption. With the help and active collaboration of two private companies (The ACI Motors and the Metal Pvt. Ltd.), two types of WBT - ACI Daedong DP488 and Metal Asia ARP – 4UM, respectively, were selected and used in this project. The financial feasibility of these machines was also evaluated under the umbrella of ASMC. Two types of seedling raising techniques were used (such as on trays and mats) for mechanical rice transplanting. Several field demonstrations of identified machines, field days, and training programs were also conducted for disseminating the technology. Rice transplanter machine has no adverse effect on the environment. Seedling raising on trays or mats is also free from chemical fertilizer application compared with traditional seedling raising techniques. The seedling raising method saves time and labor over manual seedling raising. Results show that the mechanical transplanting can reduce transplanting cost 25% to 48% depending on the seedling raising techniques.

Due to heavy rainfall early in the season (Aman season), seedling raising using mats was difficult on farmer's fields indicating needs for elevated ground level for seedling raising. Irregularity in rainfall during land preparation indicated a need for irrigation for upland and drainage for low lands that are submerged under 15-75 cm water. Over puddling of land during puddling operation causes difficulties with transplanter operation. In Boro season, cold weather causes a problem for seedling raising and nursing after transplanting. Quality seeds are needed for machine transplanting but currently are not available at the farmers' level. Due to tradition and less access to assets, markets, and machinery, women's participation in transplanter operation has been limited although the machines themselves are not a barrier for the women. In seedling raising operations women participation's has been a new activity. Women's participation has increased in seed soaking, cleaning, bagging and sprouting along with the intercultural operation of the seedbed.

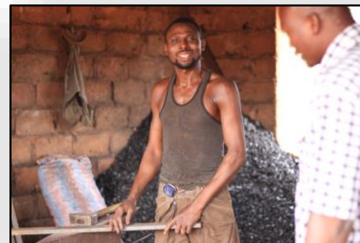
Rice Harvester

The technical performance of the two available harvesting machines, the reaper, and mini-combine harvester, was evaluated in puddled and dry conditions in the southern delta regions of Bangladesh. At the beginning of the project, promising "on-the-shelf", "in-the-field elsewhere" and best-practiced harvesting technologies were identified using a participatory value chain assessment approach involving key stakeholders. Based on technical and financial evaluations, suitable harvesting technologies were identified, tested and demonstrated on farmer's fields involving male and female farmers, local service providers, mechanics, field level extension workers, etc. Three years of research results indicate a 59% and 46% cost savings, respectively, by the mini harvesters and reapers compared to manual harvesting. Both machines are mechanically sound, robust and suitable for use at the field level. There are several mechanics and operators already trained to repair and resolve common operational problems. Since straw length is important for farmers as cattle feed and there is location-specific demand for reapers and mini-combine harvesters. Where farmers want a longer straw, they use reaper and then use a thresher, but where the farmers are not concerned about straw length, they can use mini combine harvester for harvesting, threshing, and cleaning of rice on-the-go.

Both machines are feasible for all genders. Depending on the cultural environment women in limited areas have been interested in operating the machines. It is necessary to follow some general health and safety guidelines for the harvesting of rice using the reaper and mini-combine harvester. Both harvesters can be used effectively in the Aman season, but it is difficult to use them in the Boro season in fields with water ponding depth of more than 15 cm. The researchers have developed GPS maps for the farmers and custom-hire service providers to identify areas suitable for using the harvesters. Transporting the mini-combine harvester to the fields has been challenging due to a lack of rural road infrastructure. The investigators are helping farmers in scheduling rice transplanting dates in a way that the crop in outer fields would mature earlier and can be harvested earlier than the inner fields and the harvesting machines can move to the inner fields without damaging the crops in outer fields. Local service providers and spare parts are not easily available as the machines and spare parts are imported by very few agricultural machinery importers. However, the major harvesting machinery importers and marketing companies have been contacted and requested to provide after-sale services to machine owners on time.

Conservation Agriculture and Axial Flow Pump

The innovation of conservation agriculture (CA) is to avoid repeated tilling of the soil, which saves time, energy and labor, conserving water and nutrients in the soil to support crop production. Field experiments were conducted at two different intervention areas in farmers' fields during Rabi and Kharif-1 seasons of 2017 and 2018 for testing, adoption, and popularization of different conservation machinery (CA) such as no-till planter (ZT), strip-till planter (ST), bed planter (BP) and power tiller operated seeder (PTOS) along with conventional tilling and planting of mung bean and jute. Planting costs were reduced with the CA machine (PTOS, ZT, and ST) by 35-40% for mung bean, 53% for soybean and 55% for jute compared to conventional methods. Based on two years of field experiments, less time (3-5 days) and less fuel consumption (35-55%) are required under CA tillage systems due to fewer tillage passes and cultivation operations for land preparation compared to conventional systems. About 10-16% higher grain yield was obtained from CA than conventional systems. Therefore, 36-60% of planting cost was saved by the CA machine over conventional methods. As a result, farmers have already started to purchase CA machines under the government subsidy program.



Burkina Faso trip to train staff of gender basics and conduct technology assessments on the gender sensitivity of the planter technology. Photo credit: Maria Jones.

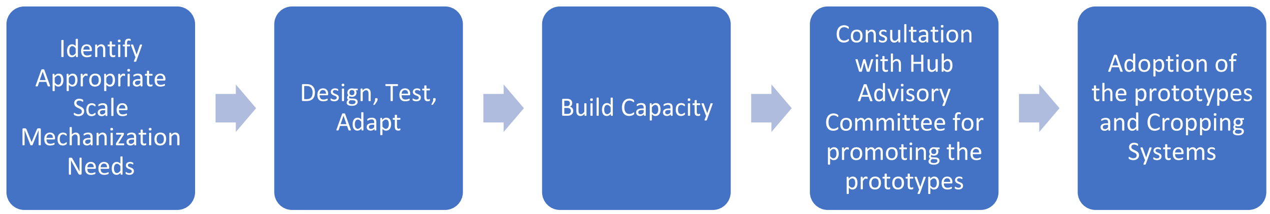
The performance tests of the axial flow pump (AFP) indicated that its capacity was 2 to 3 times higher than that of the centrifugal pump for water lifts between 1 to 3 m. Due to high discharge, AFP reduced the time required to irrigate Boro rice, wheat, and maize, with the greatest time-saving benefits resulting from when more water-consumptive crops are irrigated. Axial flow pumps can be an effective tool to mitigate the increasing energy costs derived from irrigation and to encourage the wise use of surface water irrigation for sustainable intensification in deltaic environments like southern Bangladesh.

Cambodia

In Cambodia, the share of the labor force in agriculture has been decreasing from 66% in 2009 to 41% in 2017 (MAFF, 2018) due to migrations of farmers to work in cities, garment factories or abroad such as Thailand, Malaysia, and South Korea. The scarcity of labor has generated tremendous changes in the lowland and upland farming systems as people sought to replace the lack of labor with mechanization. In the lowlands, farmers shifted from rice transplanting to seed broadcasting whereas, in the uplands, forests were converted to farmlands which generated massive degradation of the soil and other national resources. Cambodia needs to make a shift towards conservation agriculture for sustainable intensification, and this can happen through appropriate mechanization. ASMC's overall objective is to intensify smallholder farmers' cropping systems and on-farm operations through mechanization in a sustainable manner.

For a sustainable change to occur in farming systems, the private sector has to adopt the cropping systems and practices, as they play a crucial role in providing technologies, knowledge, and information needed for different value chains. The private sector can make technology more available, affordable and serviceable in local markets.

Theory of Change related to sustainable agricultural mechanization



Status and Progress of Technologies

ASMC designed and developed six mechanization prototypes including (1) conventional technology seed planter for two-wheel tractor, (2) conventional technology seed planter for four-wheel tractor, (3) no-till planter for four-wheel tractor, (4) broadcast seeder for two-wheel tractor, (5) broadcast seeder for four-wheel tractor, and (6) bucket scraper for laser land leveling. The ASMC Cambodia team completed all six prototypes and delivered them to partners for testing, disseminating, training, and adapting; made technical drawings and fabrication instructions of the prototypes; trained local manufacturers and other stakeholders; and is preparing service manuals of all prototypes for completion by September 2019.

CA cropping systems for main crops and vegetables are also progressing. Hundreds of farmers are involved in CA practice for lowland and upland crops in Battambang, Kampong Cham, and Kampong Thom province. About 30 vegetable production farmers in Battambang are implementing CA commercial vegetable home gardens.

Technology A: Seed Planter

DAEng, after assessing the existing rice seeders, developed seed planter prototypes for Conventional Technology (CT) cropping systems for 4WT and 2WT. DAEng made technical drawing and fabrication instruction of the rice seed planter for the local manufacturers and completing the service manual.

The planter sows the rice seed in the soil at equal distance and proper depth, and then covers the seed with soil. The benefits of using rice seed planter are high germination rate, lower seed rates, reduced labor requirement, and higher yield. Compare to the traditional broadcasting method which utilizes 250-350kg/ha, the rice seed planter requires only 100-120kg/ha seed. Some farmers hesitate to use the rice seed planters because broadcasting is simple, easy and faster; the price of seed is low (800-3000 riel/kg) or farmers save seed from previous years; sowing rice requires well-prepared land; the price of a seed planter is 3500 USD (4WT) and 500 USD (2WT) excluding the tractor.

The Appropriate-Scale Mechanization Innovation Hub (ASMIH)-Cambodia has promoted the use of the no-till planter in the uplands, flood plains, and rainfed lowland conditions. No-till sowing holds high promises for farmers in Cambodia. Besides time and labor savings, these machines allow better crop profitability, through yield improvement, soil and water conservation, and soil health restoration. ASMC has been testing a diversity of implements and identifying mechanisms to engage importers/retailers and local providers into conservation agriculture for sustainable intensification (CASI) transition. DAEng designed, fabricated and tested a no-till (NT) seeder prototype for rice and maize cultivation. ASMIH-Cambodia compared the performances of the DAEng NT planter with the conventional maize planter and imported NT planter used by the CASC team.

The prices of NT planters are high ($7,000 to $10,000 based on crops) making it suitable for big land size farmers, service providers or communities. Small-scale farmers would have to access the planter through service providers. However, engaging service providers into CASI is challenging because of the high investment with no guaranteed demand from the farmers. Another challenge is the availability of imported no-till planters and the lack of trust of users on the modified seeder.

To give continuity to the activities on CA and to address some of the challenges, CE SAIN launched the Conservation Agriculture Services for a Fee (CASF) in July 2018. CASF, funded by USAID, aims at engaging the private sector in the uplands of Battambang province. Several partners are involved, such as RUA, KSU, UIUC, Department of Agriculture Land Resource Management (DALRM)/CASC, DAEng, CIRAD, and Swisscontact. Swisscontact specializes in private sector engagement and implemented several activities to involve the private sector. Swisscontact engaged with a local manufacturer and importer, provided support to identify farmers' demand and built the relationship between manufacturers and service providers, and between service providers and farmers.

The activities implemented by ASMIH were also key to strengthen the national dynamic of SI. In this regard, in the coming months, CASF is launching the Cambodia Conservation Agriculture for Sustainable Intensification Consortium (CCASIC), along with the Regional Training Center on CASI at the Bos Khnor Station, General Directorate of Agriculture, Ministry of Agriculture, Forestry and Fisheries (GDA/MAFF), a part of five Agricultural Technology Parks (ATP) implemented by CE SAIN.

Technology B: Laser land-leveling
DAEng modified and tested three-bucket scraper prototypes for laser land leveling and delivered to RUA and CASC for further testing and dissemination to users. DAEng also made technical drawing and fabrication instructions that local manufacturers can use for principal guidance. The modified bucket scraper has a capacity of about seven hours/ha compared with 8-10 hours/ha of the original version. This improvement was due to stronger receiver holder stand, and because this prototype is heavier and stronger than that of the previous version bucket scraper. An undergraduate student from RUA did an internship on the laser land leveling for two months with a local service provider. In addition to learning about the technical application of the laser land leveling the student also researched and collected both primary and secondary data for his undergraduate thesis. RUA and CASC engaged the private sector to test and evaluate the efficiency of the laser land leveler and a service provider tested it in Banteay Meanchey province.

Technology C: Broadcaster
DAEng developed the rice seed broadcaster and compared its performance with hand broadcasting. DALRM/CASC team jointly with the Australian Centre for International Agricultural Research funded Cambodia Sustainable Intensification and Diversification (CAMSID) project, started additional studies in May and June 2019 with the results expected in December 2019. The experiments will compare the performances of seed broadcasters, with various rice seeders and traditional hand broadcasting. The team will assess rice emergence, final rice plant density, tillering rate, yield, and the prevalence of weeds and disease.

Technology D: Roller-Crimper
Since the early stage of CA implementation, GDA/DALRM locally produced a roller-crimper but mainly used on the experiment station. Through ASMC, DAEng developed a roller-crimper along with an NT seeder with a roller in front of the planter to terminate the cover crops at sowing time in a single pass. A roller crimper helps improve the overall efficiency of the cropping system by reducing the number of passes between rolling down the cover crop and sowing the main crops through the mulch of the cover crops. It also eliminates or reduces herbicide use, with the crimped product, mulch, and dead roots,

contributing to soil health enhancement, improving water infiltration and retention and soil organic carbon sequestration. The DAEng crimper for 4WD tractor costs approximately $1,800. The challenge is the engagement of the private sector like agricultural machinery dealers and service providers. ASMIH-Cambodia with CASF is creating demand for CA machinery like promoting the use of roller crimper with NT seeders to farmers, national and provincial government, and private machinery service providers. The two teams are also training Cambodians in machinery for conservation agriculture production systems focused on replacing soil degradation in conventionally tilled production systems with the CASI system.

Technology E: Oggun Tractor

ASMC invited the entrepreneur, Horace Clemmons to present the open-tractor idea in the 2018 American Society of Agricultural and Biological Engineering. CE SAIN with ASMC and CASF picked up the idea and imported an open tractor, the 'Oggun' with a USDA-ARS crimper and NT Morrison seeder. The Cambodian team named the Oggun tractor the 'A-Click' tractor and convinced a manufacturer to invest in manufacturing the first A-Click tractor in Cambodia. Also, a Ph.D. student and his team are evaluating the A-Click's performance on Conservation Agriculture for Sustainable Intensification, while estimating its cost to manufacture in Cambodia. In July 2019, some members of ASMC team-Cambodia visited the Oggun assembly plant in Paint Rock, Alabama, and the United States Department of Agriculture, Agriculture Research Service Soil Dynamics Lab that specializes in designing, prototyping, and testing conservation agriculture machinery.

Technology F: Vegetable Hand Tools

More than 30 types of hand tools brought from the US, EU, Africa, and Asia were introduced to farmers and tested to identify which are appropriate, best, and effective in farming. Time and labor savings have been considered as keys for adaptation of the hand tools in the commercial vegetable production. Some of the tools tested were handy twine knife, over the shoulder harvesting bucket, section garden hoe, single tine cultivator, cape cod weeder, three-tine cultivator, short single tine cultivator, push-pull hoe, long batwing hoe, collinear hoe, and digging tool.

Ethiopia

In Ethiopia, grains like teff, maize or wheat are an essential staple food of farmers and play a significant role as an income stream when sold at local markets. Therefore, the ASMIH has focused most of the technologies around the improvement of the production and postharvest management of maize. During harvest, maize is shelled by hand by the farmer and at least three to four more people from his family or other farms in his community (kebeles). Grains are usually stored in rudimentary structures that don't provide a proper seal to avoid pest entrance.

The wooden wings of the traditional animal drawn implement is replaced by metal, which is aimed at reducing the number of repeated plough during seed bed preparation and the reducing the amount of weed. Photo credit: Yonas Degu.

Farmers in the Amhara Region lack opportunities to grow and produce food during the dry season due to the lack of water-lifting technologies and inaccessibility of water sources. Utilizing them can help farmers grow a variety of vegetables for self-consumption and/or to create an extra income from their farm. Lack of availability of inputs such as fertilizers and pesticides are common concerns for small-scale farms. Additionally, when crops are grown during the dry season, it is common to see significant soil moisture loss. During the rainy season, the rainfall causes losses of soil nutrients due to poor soil and water management practices to harvest and utilize the rainwater. Conservation agriculture (CA) can help mitigate these losses. Competitive use of mulch (for animals and soil cover) and lack of appropriate tools are among the challenges related to CA practice in the region.

In the Amhara Region of Ethiopia, animals play a significant role in agriculture by providing draft power for transportation and preparation of land for agricultural purposes. Usually, each farm will have oxen to pull equipment with yokes that in many cases don't have the correct design or are too heavy which affects its performance or causes unnecessary fatigue. Based on these issues, the ASMC has established an Innovation Hub at BiT to focus its work on the development and testing of maize shellers, metal silos, animal draft powered equipment (yoke), water lifting technologies, and Conservation Agriculture.

Maize Shellers

Two engine-powered maize shellers (one designed and fabricated at BiT, and another one purchased in Addis Ababa) were tested utilizing two different commonly planted maize hybrids in 35 farms from five kebeles (communities) that were part of two woredas (districts were the communities administratively belong). The tested maize shellers help avoid quality loss of the kernels due to the potential damage during hand-shelling which makes the kernels more susceptible to insect attacks and mold growth during storage. Also, it saves time for the farmers to invest in other activities. Additionally, they required limited maintenance, the operation is simple, and can be run by men, women, and youth. This technology has been promoted and demonstrated to 546 farmers (165 of them were females) from five kebeles and to custom hired services providers (with more than 60-hours of training and connection to the farmer communities). The main limitations for scale-up are purchasing cost so a specific number of service providers can utilize the equipment for free until they can generate revenue to purchase it and accessibility to the technology. Therefore, its fabrication has been performed at lower cost by two TVETS technical, vocational, and educational colleges (trade type community colleges) and five private enterprises to provide support on operation and maintenance to the custom-service providers that can use the technology as hires to farmers. These small enterprises that are linked to TVET's for investment in entrepreneurial activities that provide services to communities can receive some financial assistance from the Ethiopian government. The designs have been adapted so they can be operated by all genders and by youth. However, the design needs to be reduced in size to make it easier for handling and transportation.

Animal Draft Powered Equipment (Yoke)

Yoke fabrication training was developed by BiT in conjunction with Tillers International with the goals of teaching blacksmiths and private enterprises how to fabricate economically feasible, improved yolks as a business and to educate farmers on how their usage can improve the performance of animal draft power during agricultural activities. The two-day training sessions were developed in the two locations of Dangila Zuria Woreda (Dangishita kebele) and Dangila town and had ten farmers (three of them were females), two government extension workers, two blacksmiths, and one enterprise owner as participants. The yokes were fabricated by utilizing locally available low-cost materials (like PVC tubes) and techniques that are easily performed by non-technical persons making suitable for farmers and potential services providers. The main limitation of the scalability of this technology is the lack of tools for fabrication and maintenance by the farmers. However, blacksmiths and private enterprises were trained on fabricating the improved yolks at a lower cost, so farmers don't need to fabricate their tools. The use of improved yolks does not have a direct economic effect on the farmers. However, its benefit as it was shown during the training with a quality comparison between the traditional and improved yolk designs, is that the animal will have a better performance which results in less fatigue and potential injuries. This equipment is designed to be operated by all genders. However, the activities involved with animal draft are typically performed by males.

> This technology can improve efficiency during land preparation which potentially can allow the farmer to save some time for other activities.

Metal Silo

Metal silos were designed and fabricated at the ASMIH by BiT students as part of their research projects. Field demonstrations were conducted at the Dangista Kebele of the Dangila Zuria Woreda to train 166 farmers on its usage and prevention of grain quality loss during storage. The capacities of 0.25 to 1 MT can easily accommodate the households of the small-scale farmers in the same location as the traditional rudimentary storage without causing any adaptation and no training is necessary. The scalability of this technology-focused on connecting private enterprises for potential fabrication and sales of metal silos to small-scale farmers. The main limitation of this technology is its purchase cost. Therefore, a potential micro-credit system has been discussed that can connect the farmers to finance the purchase of agricultural equipment including the metal silos. Also, the utilization of the metal silos can result in a better quality of grains (maize) that during sales at the local market resulting in higher incomes when compared with end-quality after storage in the traditional way. Metal silos may also reduce the need for insecticides due to the physical barrier preventing insects from reaching the grain. The metal silo can be fabricated utilizing locally available metal sheets. It is necessary that the proper metal bending and welding equipment is utilized for optimal quality.

Water Lifting Technologies and Conservation Agriculture

The BiT has implemented along with other partners, testing the water-lifting technologies and conservation agriculture (CA) by growing a local variety of onions at 34 on-farm locations in Dangishta during the dry season (December to March) with the participation of both male and female farmers. The water system has a solar-powered portable water pump (maji pump) that feeds into a tank (1,000 L capacity) which feeds water by gravity to a drip irrigation system set up in the plots. The effective size of these plots was generally between 50 to 70 m^2. As a preliminary conclusion, these initial experiments indicate that mulching can increase yield and save water. A second experiment was conducted growing peppers during the wet season and with irrigation during the dry season. The results showed that irrigation increased pepper production 12 % in the first year and 51 % in the second year. During the rainy season, CA practices reduced nitrogen loss and increased phosphorus dynamics within the root zone. This water lifting technology utilizing CA is well suited to the small-scale farmer and its simple operation can be conducted by men, women, and youth. The main limitation of this technology is the cost of the maji pumps and tanks. However, results obtained during testing suggests farmers are willing to invest in micro-financing systems to acquire them. Currently, they are loaned out until the farmer generates enough revenue to purchase them. There is a limitation on the local availability of the pumps, but the ASMIH has been looking for other available pumps. Despite the simple mechanism of the pump, maintenance can be difficult for the farmers, therefore, technical assistance has been provided to teach them the basics for simple repairs. The water lifting system with CA reduces water loss and runoff of the soil nutrients. The maji pumps run on solar power, therefore, no fuel or external electricity is needed. The Ethiopian government extension agriculture team was trained by BiT on its operation and common maintenance issues so they can assist the farmers when needed.

Capacity Building Engagement

The ASMIH has provided technical training on the benefits of agricultural technologies that allow farmers and youth to improve their agricultural practices. At the same time, it has allowed rural communities to connect as a group to acquire or develop technologies more efficiently. Additionally, it has connected academic technical expertise to help solve their issues related to agricultural production in many cases by providing funding opportunities to introduce students to agricultural mechanization and to be recruited

Also, it has provided improved designs, tools, and technical support for them to improve this business of fabrication. Finally, it has motivated through its participation in different scientific and government meetings and forums - for example, co-organizing the 3rd National Agriculture Mechanization Forum.

for graduate studies in technical areas. It has provided the necessary tools to help BiT established themselves as one of the key locations to develop extension and research programs in agricultural mechanizations. Also, ASMIH has provided a connection between farmers and services for the fabrication of agriculture machinery/tools.

Gender Engagement

In ASMIH, 168 women farmers have been trained or intentionally engaged directly in the design and testing of new technologies. Also, ASMIH gender expert and its students have collected data and have direct engagement on the activities of the different training sessions.

Business Models/Private Sector Engagement Efforts

Currently, there are six private enterprises engaged in the manufacturing of different technologies and multiple private sector partners have participated in different training sessions. One of the main skills that have been gained is the focus on the fabrication of agricultural tools and equipment. Also, they have gained knowledge of the opportunities to provide custom hire services to farmers from technical and economical perspectives. ASMIH is currently utilizing the business models called the "rent to own" approach. However, its effectiveness has not been tested yet as it is still under implementation. Additionally, based on the results of the feasibility and utilization trends of some of the technologies, other approaches will be developed. In Ethiopia, the role of the private sector in agricultural mechanization is very limited. The implementation of ASMIH is pushing into involving private sectors in the manufacturing, distribution, promotion, and usage of technologies. For example, there is support on the establishment of SMEs for agricultural mechanization technologies by giving business foundation training for the unemployed youth and local enterprises already engaged in other related businesses. Currently, the involvement of the public sectors has been limited, but it will be the focus by engaging it to promote the business models to newly established companies by providing appropriate infrastructure, facilitation of loans, local subsidies and creation of a market. The goal is to align with the government priority of agricultural lead industrialization by facilitating the acquisition of foreign currency during the procurement of services and technologies.

Burkina Faso

The main cash crops in the Hauts-Bassins Region of Burkina Faso are corn, cotton, soybeans, peanuts, and sesame often integrated with livestock production including cattle, sheep, goats, and poultry. Small landholders typically farm 2 to 3.5 ha; mid-size farms are about 7 ha, and large farms are 10+ ha. About 70% of farm work is done manually, 29% by draft animals (oxen) as their primary power source and only about 1% of farmers use mechanized power units solely for primary tillage. The other labor-intensive fieldwork of seeding, weeding, crop care, and harvesting is typically done by hand. This project focused on maize as the primary crop.

Five farmers were chosen to use the ASMC tillage kit for production in the coming season in Burkina Faso. Photo credit: Michel Kere.

Innovation Hub

The main philosophy of the Innovation Hub is to involve local stakeholders including farmers, artisans, researchers, students, and extension professionals to identify problems, innovate solutions and demonstrate their effectiveness to create a sustainable ecosystem of innovation so that solutions can be found using local experiences, skills, and resources. Specifically, the Hub has identified key issues such as land preparation, planting and weed control, animal nutrition and comfort, and lack of nutrition especially during the dry season as key issues facing farmers in Burkina Faso. The Hub help develop a set of animal-drawn, locally fabricated tools using locally sourced materials; system and equipment to make silage; ergonomically designed yokes to improve animal comfort and productivity; and a solar-powered drip irrigation system to grow vegetables during the dry season as a source of nutrition for the households. These scalable innovations will possibly improve farmers working conditions, rapidly increase crop productivity (especially maize), significantly reduce food insecurity and promote sustainable intensification of production agriculture in Burkina Faso.

Mechanization

A system of appropriate-scale mechanization that includes rippers, planters, and cultivators has been developed, field-tested, and adopted by many farmers. Many blacksmiths have been trained to build these tools. As a result of a baseline survey, improvements were needed in land preparation, planting, and weeding operations. Our work aimed to improve the tillage system and set up an integrated system called ripping-planting-weeding. Deep plowing system (30-40 cm), had resulted in low soil fertility, therefore, it was important to find a new way for land preparation. The ASMC developed a tool called ripper for minimal soil disturbance (5-10 cm depth). The ASMC designed and adapted a planter design based on the Tillers International prototype. Local blacksmiths were trained to fabricate the ripper which was tested at our field Hub location (Mr. Ly's farm) in 2017. The prototype was approved by the ASMC research team and now this technology is ready for scaling. In total, 25 farmers used the technology in 2018 and the feedback showed that the planter can have a greater impact on crop production in Burkina Faso. While we are working on an integrated system: ripping-planting-weeding; the planting is the main operation for most farmers.

We also entered a national competition organized by the National Research Fund (FONRID) and won first place for our planter design. We were awarded 18,000 USD for scaling. A total of 20 farmers used our planter during 2018 and produced maize on about 40 ha of land. Among those farmers, six were female farmers. The ASMC planter is now well known and is shown during the national symposium in Ouagadougou (from 20 to 25 October 2018). In total, 15 planters have been ordered to be used for the next growing season. Steps have been taken to commercially manufacture seed metering plate using injection molding technology by a local manufacturer. This will be a significant step toward scaling-up the planter.

Planter (Sayaogo, 2018)

Planting operation at Koumbia (Millogo, 2017)

Ripping (Millogo, 2017)

Animal Nutrition and Comfort

Since these tools are animal-drawn, animal comfort and nutrition are critical to successfully adopt this technology. To achieve this the following critical steps have been taken:

<u>Yoke making</u> – multiple hands-on training sessions have been held to train farmers and blacksmiths to build ergonomically comfortable yokes. These have been well accepted by farmers.

<u>Silage making</u> – A system for silage making was introduced that included designing and building a forage chopper and storing chopped stalks in poly bags in plastic containers. Students are completing a study to analyze the quality of silage and their acceptability by animals.


A chopper (left) and whole maize cut by the chopper (right) (Sayaogo, 2018 Koumbia)

During dry season animals are left to roam and fend for themselves. Consequently, they are weak and suffer from malnutrition. It was decided that maize stalks can be chopped and ensiled to provide feed for animals who would be corralled and not allowed to roam. Thus, their manure could be collected and composted and used as organic fertilizer to improve soil health. The ASMC developed a forage chopper for making silage and to improve animal nutrition. The chopper was designed by Tillers International and was built by local artisans trained by Tillers. Silos were filled with chopped material and sealed in Sept 2018 until March 2019. Data are being analyzed to assess silage quality. However, 8 choppers were ordered by the SIIL project at ILRI in Burkina Faso for village community use in their project area indicating good collaboration between ASMC and a SIIL sub-project.

Solar-powered drip irrigation system for vegetable production during the dry season

The objective was to design, implement and test a drip irrigation system powered by solar PV to grow vegetables during the dry season. This system was designed to meet smallholders' farmers' needs who by mechanizing their agriculture system could save time to produce vegetables for family consumption. The irrigation system included: 1) a 7 meters deep well and a helical submersible pump (Lorentz PS2-200 HR 07); 2) two solar panels of 130 W each; 3) 2000 liter poly water tank located at a height of 2 m; 4) a drip irrigation system including main and laterals with emitters. During the 2017-18 dry season vegetables were successfully grown in the experimental plots. These vegetables included onion, cabbage, and tomato under mulch. During the 2018-19 dry season maize was planted intercropped peanut, mung bean and green bean under mulch. Both years were highly successful. It was concluded that the drip irrigation system caused less drudgery for women and required limited time for the operator.




A 7-m deep well and 2 solar panels (left), water tank of 2000 l (center left) and experimental plots (right) (Millogo, 2018)

Gender integration
Based on a focus group study and a baseline survey the following key gender issues have been identified: a) Improving nutrition; b) Increasing household income; c) Increasing access to credit. Many of the project innovations have the potential to directly impact these issues. We are in contact with local banks to explore how we may increase access to credit for women. A study is underway to assess the impact of planter technology from a gender perspective.

At least 360 women have been involved in the various activities of the project (making tools, testing, students, using tools, gender training, focus groups survey and baseline survey). In Burkina Faso, there is a law that indicates that women should be represented in all groups for any activity and 30 percent is a minimal number.

Capacity building and engagement
Multiple short courses, training sessions, and seminars have been conducted on topics such as yoke animal nutrition, post-harvest losses, and silage making. UPB is in the process of creating an MS degree program in agricultural mechanization as well as in irrigation. The project is linked to communities through leader farmers. Presently, the project has 3 demo sites and 25 farms across the project area (Hauts-Bassins Region). The ASMC is working directly with the local banking system and farmers' organizations that are members of the Advisory Committee where we continue to discuss innovations and related problems. The collaboration of small enterprises is through making the tools and working with blacksmiths organizations that are private enterprises. The project included at least 27 students for 45 days in fields and 10 students for the required master thesis fieldwork. Students know the process of the innovation; have a relationship with blacksmiths and farmers. They can work with a blacksmith to design, fabricate, and to repair all tools made by the project. The ASMC is developing the master program for mechanization which will be included in the training curricula. The youth engagement was through engaging young farmers.

Business model/private sector engagement efforts
The ASMC project has engaged 16 private partners (local banks, local blacksmiths and farmers' organizations) in the various aspects of the project. We need to explore microfinancing and other ways to have credit available to women farmers as well as explore opportunities for government subsidies.

8. Future Challenges and Opportunities

- Emphasize business models for scaling up and out (Private vs Public Sectors) (SwissContact collaboration)
- Review and evaluate degree programs at respective universities in each country relative to providing effective learning on agricultural mechanization and explore the potential for degree programs that combine technology and business learning
- Review short term training learning objectives that address the broader context of technology interventions and impacts on productivity, environment, economics, and the human condition.
- Emphasize the need to publish research for the benefit of staff/faculty and students
- Continued refinement and application of Gender Technology Assessment tool for technologies
- Expanded youth engagement relative to exposure to agricultural mechanization and participation in agricultural production systems
- Further integration of agricultural mechanization into policy frameworks
- Empower farmers to participate more actively in post-farm production enterprises
- Leverage linkages with NGO's and research institutes to take advantage of experience/knowledge in mechanization (CGIAR centers, CIMMYT, FAO, Institutes)
- Investigate solar power options and electric vehicles (MSU-Solar-powered Traction Unit)
- Incorporate the use of Information Technologies

a. Leverage precision and digital agriculture and system evaluation for effective decision-making

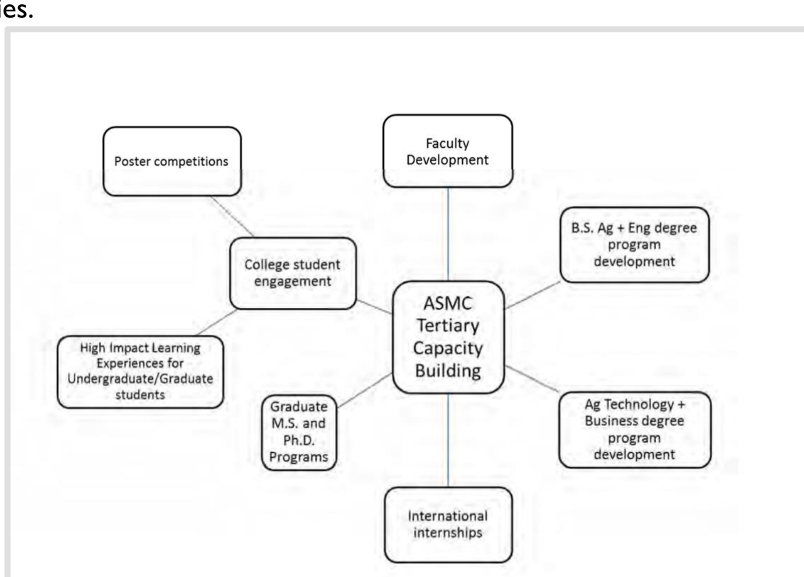
Technology Readiness Assessment

In reviewing the technologies identified in each country for potential scaling up and out, one challenge is to assess their relative level of readiness/sustainability/resilience for deployment on both a country and regional basis. There is a need to carry out a "Technology Readiness Assessment" associated with each of the technologies developed. Questions to be addressed in the assessment should include the following:

- What is the current level of deployment of each technology?
- What results of metrics are available to measure the potential impact of this technology in the context of productivity, environment, economics, social and human conditions?
- What level of participation from the private sector has been established in promoting the deployment of each technology?
- What methods of deployment have been established so far? (service provision, farmer cooperatives, etc.)
- What level of infrastructure has been established for this deployment to ensure its sustainability (spare parts, maintenance capacity, etc.)
- Has a provision been made to train users of the technology?
- What is the potential for each technology for regional expansion of its deployment? (e.g. West Africa versus Burkina Faso)
- What efforts have already been made to promote changes to government policies to facilitate technology procurement and deployment? (reduced import duties?)
- Are there needs for other technologies to be identified/developed/tested/evaluated?
- Has a gender assessment relative to the use of the technology been carried out, and if so what are the results?

Tertiary Capacity Building

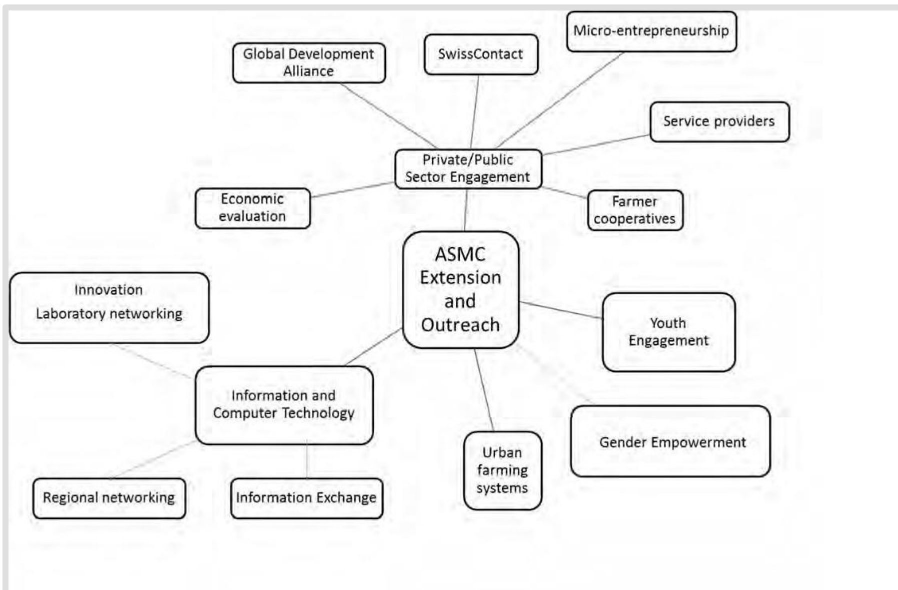
Capacity building at the tertiary level is critical to the development and expansion of appropriate technology adoption. The model of establishing Innovation Hubs at a University in each country has facilitated and helped promote such capacity building. However, challenges occur because of constraints and academic structures within these different institutions that may be tied to traditional systems of operation. The diagram below highlights some key topics for addressing tertiary capacity building in the respective countries.



Apart from targeting the creation of B.S. degree programs combining engineering and agriculture, there is a strong need to develop degree programs that combine business and technology, graduates from which will be able to address the development and scaling of suitable technologies. Other activities include college student engagement to help them expand their skills and knowledge, and this may include providing international internships. Faculty development remains an important need and can be facilitated via collaborations amongst the various U.S.-based institutions and in-country institutions.

Extension And Outreach

As mentioned above, there are some topics related to extension and outreach that present challenges and opportunities. The figure below includes some of the key areas that should be investigated and most of which have already been highlighted. One area that has not been addressed is that of urban farming systems. Its application in metropolitan areas of some of the big cities could be expected to have a big impact. However, it is a relatively unexplored topic and therefore it may be viewed as a big challenge to implement.



9. Publications

Bangladesh

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Ethiopia

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15. Vinsoun Millogo, Barro Albert, Dao Begue, Sayaogo Boureima, Toundji Olivier Amoussou, Kéré Michel, Robert Burdick, Timothy Harrigan and Ajit Srivastava (2019). Test of the draft animal planter designed and built by appropriate scale mechanization consortium for improving maize planting system (Ongoing manuscript).
16. Kéré Michel, Vinsoun Millogo, Bonzi Schemaza, Ganou Fatoumata, Toundji Olivier Amoussou, Timothy Harrigan and Ajit Srivastava (2019). Vegetable production under a drip irrigation system and the effect of cover rice straw on water management and weed control (Ongoing manuscript).
17. Manzamasso Hodjo, Michel Kere, Vinsoun Millogo, Ajit Svrivastava and Benjamin Schwab (2019). Demand for Agriculture Mechanization in the Hauts-Bassins Region (HBR) in Burkina Faso.
18. Maria Jones (2019). Gender Technology Assessment. Appropriate Scale Mechanization Consortium, Burkina Faso: Planter Techonology University of Illinois at Urbana Champaign.
19. ASMC Burkina Faso (2019). Science Committee Report ASMIH: Burkina Faso July 15, 2019.
20. Robert Burdick, Ashley Juengling and Timothy Harrigan (2017). BIFAD Meeting technology, Ox-drawn Row Crop Planter.
21. Blog article 1 (Tim Harrigan): Animal Traction Technology in Burkina Faso
22. Vinsoun Millogo and Michel Kéré (2016). Appropriate Scale Mechanization Consortium (ASMC) Update from Polytechnic University of Bobo-Dioulasso Burkina Faso. Symposium Mechanization & Postharvest Opportunities for Smallholders in Sustainable Agriculture. 22-23 July at University of Illinois Urbana Champaign.
23. Vidéo (Tim Harrigan): Animal Handling Training Video
24. Vidéo (Tim Harrigan): Innovations in Animal Power
25. Video (Tim Harrigan): Training Oxen, Training Farmers
26. Video (Tim Harrigan): Affordable Forage Chopping for Small Holder Farmers
27. Video (Tim Harrigan): Conservation Tillage, planting, and cultivation in Burkina Faso
28. Manzamasso, Hodgo, Michel Kere, Vinsoun Millogo, Ajit Srivastava and Ben Schwab. Demand for Agricultural Mechanization in the Houts-Bassin Region (HBR) in Burkina Faso. Manuscript submitted (2019) to the African Journal of Agricultural and Resource Economics.

CONSORTIUM 3

policy research

Consortium 3

Policy Research Consortium

1. Lead Institution: Rutgers University

2. Research Team:

- Lead Investigator:
  - Dr. Carl E. Pray
- Co-Investigator:
  - Dr. Anwar Naseem

3. Executive Summary

Rutgers University (RU) leads the consortium to support the learning agenda on policy, systems analysis, and implementation. The aims of the consortium are to develop a clearer understanding of contemporary agricultural and structural transformation. Develop and utilize specific set of indicators to quantify the impact or progress of key Global Food Security goals. Understand how agricultural and food policies help to enable and contribute to agricultural transformation.

4. Project Partners

- International Fertilizer Development Center (IFDC)
- Michigan State University
- Montana State University
- Northwestern University
- Tufts University
- University of Florida
- African Economic Research Center
- University of Rwanda
- Universite Gaston-Berger

5. Project Goals and Objectives Goal:

Overall Goal

The FTF initiative has an overarching objective of inclusive economic growth, particularly agricultural growth and rural development. Rutgers University—with support from USAID under the FTF initiative—leads a multi-institutional consortium of researchers based in the U.S. and FTF countries to conduct a series of impact studies related to agricultural and food security policy.

> The Consortium, which was formed in late 2014, brings together leading experts in agricultural development policy and aspires to be a forum for independent and innovative research on policy analysis.

Overall Objectives

Objective 1: The first critical area of emphasis for the Rutgers FTF Consortium research agenda is developing a clearer understanding of contemporary agricultural transformation and how to manage it for the greatest societal benefit.

Objective 2: The second critical area of emphasis for the Rutgers FTF Consortium research agenda is understanding how agricultural and food policies and policy systems help enable and contribute to agricultural transformation.

6. Accomplishments & Utilization of Research Outputs (Country-Level)

1. Visit by Naseem, Pray and Nagarajan to Kenya to consult with a variety of agricultural input industry players as part of their study on impact of changes of input policy in Kenya and East Africa in general.
2. Visit by Naseem and Weatherspoon to Rwanda to collaborate with Consortium members Niyitanga and Nsabimana, and field visits to CIP areas to better understand the context for the price/nutrition work.
3. Funding of 15 research theses by African Economic Research Consortium (AERC) sponsored students, as well as three research projects by AERC researchers.
4. Publication of six papers by different Consortium members in a special issue of Journal of Agribusiness in Developing and Emerging Economies highlighting the research that has been done.
5. Publication of an additional three peer reviewed papers in high impact journals.
6. Presentations at various academics forums, such as the annual meetings of the Agricultural and Applied Economics Association (AAEA), the International Consortium of Applied Bioeconomy Research (ICABR) as well at seminars at IFPRI and University of California.
7. Publication of 7 policy briefs which will be made available to policy makers and other interested parties.
8. Organizing a listening session with USAID to present the work of the Consortium but also learn more from USAID/BFS about their needs for ideas and analysis that can strengthen their program in the near future. This activity is planned for October 28-29, but required considerable planning during FY 2019.

Dr. Florent Tivet teaches about soil health during the SAIN conference. Photo credit: David Ader.

7. Publications

1. Masters W.A. (2019), Undernutrition and the dietary transition. University of California Network on Child Health, Poverty and Public Policy, 6 September 2019.
2. Masters W.A. (2019), Affordability of nutritious diets in Malawi, Tanzania, Ethiopia and worldwide. Partners meeting convened by the Feed the Future Innovation Lab for Nutrition, 6 August 2019.
3. Masters W.A. (2019), Access to nutritious diets as a policy indicator for agricultural transformation and healthy food systems. ICABR session on Food Systems, 6 June 2019.
4. Moss and Schmitz (2019) estimate the distribution of benefits from the introduction of technological innovation.
5. Nagarajan et al. (2019) evaluate the impact of policy changes in the seed sector on productivity.

CE SAIN

CE SAIN

Center of Excellence on Sustainable Agricultural Intensification and Nutrition (CE SAIN)

1. Lead Institution: The Royal University of Agriculture

- U.S. Collaborating Institution:
  - Kansas State University

2. Leadership Team:

- Lead Investigators:
  - Lyda Hok, Director
  - Thyda Laing, Development Manager
  - Pisey Sar, Project Reporter
  - Manuel Reyes, SIIL Regional Coordinator

3. Executive Summary

CE SAIN – housed in Cambodia's Royal University of Agriculture (RUA) – helps improve food and nutritional security in Cambodia by supporting agricultural research and education while fostering innovation. CE SAIN's goal is to foster private sector innovation, agricultural research, education and training, and public sector capacity building through improved collaboration and knowledge sharing that is focused on improving food and nutritional security while enhancing quality of soil, water and biodiversity. CE SAIN's three core objectives are: a) coordinate and leverage Innovation Labs and other USAID-funded SAIN activities, b) build human and institutional capacity of the RUA, and c) establish Technology Parks to showcase high-potential technologies and strategies to sustainably intensify smallholder farming systems.

Farmer training on agricultural diversification conducted at the Battambang CE SAIN Technology Park. Photo credit: Tom Gill.

4. Project Partners

- Agricultural Development Denmark Asia (ADDA)
- Agricultural Research for Development (CIRAD)
- Agri-Smart
- American Soybean Association
- ATEC-Biodigester Company
- Auburn University
- AVRDC-World Vegetable Center
- Can Tho University
- Center for Sustainable Agricultural Machinery, United Nations Economic Social Commission for Asia and the Pacific
- Cleber
- Danfoss
- Department of Agricultural Engineering (DAEng)
- ECHO Asia
- Epsilon Sigma Phi
- Fish Innovation Lab (Mississippi State)
- Food and Agriculture Organization (FAO)
- Horticulture Innovation Lab (UC Davis)
- Institute of Technology of Cambodia (ICT)
- Integrated Pest Management Innovation Lab (Virginia Tech)
- International Development Enterprise (IDE)

- International Fertilizer Development Center (IFDC)
- International Livestock Research Insititue (ILRI)
- International Rice Research Institiution (IRRI)
- Kasetsart University
- Larano
- Livestock Systems Innovation Lab (University of Florida)
- Medivet Group
- Michigan State University
- National Academy of Sciences (NAS)
- North Carolina A&T State University
- Oregon State University
- Pennsylvania State University
- Project Everest
- Southeast Asian Regional Center for Graduate Study and Research in Agriculture (SEARCA)
- Texas A&M University
- Tufts University
- United Service Foundation
- University of Connecticut
- University of Illinois, Urbana Champaign
- University of the Philippines, Los Banos
- University of Tennessee
- USDA-ARS-Coastal Plain Soil, Water and Plant Conservation Research Lab
- USDA-ARS-Grassland Soil and Water Research Lab
- USDA-ARS-National Soil Dynamics Lab
- USDA-FAS
- World Agroforestry Center – Philippines
- World Fish, Malaysia
- World Vision USA

Target Country Partners

Cambodia

- Conservation Agriculture Service Center (CASC)
- Ministry of Agriculture Forestry and Fisheries (MAFF)
- Ministry of Education, Youth, and Sport (MoEY)
- Royal University of Agriculture - Phnom Penh
- University of Battambang
- Feed the Future Innovation Labs (e.g. Horticulture; Livestock Systems; Integrated Pest Management)
- Swisscontact

5. Project Goals and Objectives

Overall Goal

The Center's goal is to serve as an entity that fosters private sector innovation, agricultural research, education and training, and public sector capacity building through improved collaboration and knowledge sharing that is focused on improving food and nutritional security while enhancing quality of soil, water and biodiversity.

Overall Objectives

Objective 1: Coordinate and leverage Innovation Labs and other USAID-funded SAIN activities.

Objective 2: Build human and institutional capacity of the RUA.

Objective 3: Establish Agricultural Technology Parks to showcase high-potential technologies and strategies to sustainably intensify smallholder farming systems.

6. Overview of Activities

Overall Approach

Engaging Innovation Labs

Six Feed the Future Innovation Labs are currently engaged in Cambodia, including: Sustainable Intensification, Horticulture, Integrated Pest Management, AquaFish, Nutrition, and Livestock Systems. The common goal of the innovation labs is to conduct research and build capacity to address food and nutritional security in Cambodia. The innovation labs partner with local academic institutions, government, and farmers to pilot promising technologies to get them ready for wider introduction by private sector, development partners and the government.

> CE SAIN plays a key role in coordinating projects that are being implemented by Innovation Labs and enhancing the development of best practices on sustainable agricultural intensification and nutrition (SAIN) through technological interventions, agricultural research, and an innovative model farming system to be utilized in extension activites.

Technology Development and Assessment

Technology Parks

CE SAIN has established five Technology Parks in the following locations: RUA in Phnom Penh, Bos Knor station in the Kampong Cham province, Reasmey Sophornna High School in the Kampong Thom province, Toek Vil Agricultural Research Station in the Siem Reap province, and the Research and Training Farm at the University of Battambang (UBB). These Technology Parks showcase high-potential technologies and strategies to sustainably intensify smallholders' production systems.

The Technology Parks demonstrate promising technologies and production methods to attract private sector participation within research and farmer networks. The Technology Parks are also a focal point to organize innovation fairs, field days, and workshops to engage all actors along the agricultural value chain from government workers, farmers, to agribusinesses. Four of the five Technology Parks are located in farming communities.

In addition to showcasing SAIN best practices, the Technology Parks also serve as a/an:

- **Learning platform**: CE SAIN organizes field days to demonstrate promising technologies and strategies that are profitable for smallholder farmers. The CE SAIN Technology Parks feature a farming systems model that can be adopted by smallholders in the area. The model demonstrates various promising technologies and strategies based on the local context to showcase best management practices of agriculture.
- **Research farm**: Scientists, researchers and interested stakeholders can visit and test their new innovations in the Technology Parks with cooperation and support from CE SAIN and RUA.
- **Internship venue**: The students of RUA and other relevant universities who study agriculture can access the Parks for their internship program and final thesis development.
- **Synergy program with USAID-funded partners**: The parks are open for interested USAID-funded partners to engage with CE SAIN.
- **Private sector engagement platform**:The Technology Parks are available for private sector collaborators to test new innovations, researching and demonstrating technologies and

equipment that have the potential to increase yields and income for smallholder farmers in the area while enhancing ecosystem services.

7. Accomplishments & Utilization of Research Outputs (Country-Level)

2017

- Five Technology Parks were established in the following locations: RUA in Phnom Penh, Bos Knor station in the Kampong Cham province, Reasmey Sophornna High School in the Kampong Thom province, Toek Vil Agricultural Research Station in the Siem Reap province, and the Research and Training Farm at the University of Battambang (UBB). These Technology Parks showcase high-potential technologies and strategies to sustainably intensify smallholders' production systems.
- More than 20 technologies and innovations were demonstrated at the five TPs in FY 2017. Smallholder farmers, local partners, private companies, students, and researchers were invited to visit, engage with farm managers, and exchange knowledge.
- Seventeen interns and volunteers, mostly comprised of recent university graduates and fourth-year university students, were recruited to work at the TPs in FY 2017. These experiences allowed participants to gain in-depth technical and practical knowledge of field implementation of agriculture projects as a supplement to their classroom studies.

2018

- CE SAIN co-hosted the First International Sustainable Agricultural Intensification and Nutrition Conference and Field Trips in January 2018 in collaboration with the SIIL. One hundred sixty-five individuals from 16 countries attended the conference, and over 60 individuals participated in the field trips.
- Seventeen collaborative research and demonstration projects were initiated with universities, private sector companies, and other funded projects.
- Promising technologies from U.S. Government-funded projects and other international organizations were showcased in the five Technology Parks. Specifically, 22 technologies and research trials were demonstrated along with strategies to sustainably intensify smallholders' production systems. These are all accessible to farmers, students, researchers, local partners, and private companies. More than 1,273 people (38% female) visited the technologies this year.

2019

- CE SAIN collaborated with 14 research institutions, 67 researchers and two non-profit organizations and three private sectors at the ATPs. CE SAIN hosted a field visit for Can Tho University and signed an MOU for the Commercialization of Aquaculture for Sustainable Trade (CAST) project. The role of Can Tho is to support CE SAIN in pond renovation and building technical capacity in aquaculture for RUA faculty and staff.

- Disseminated available data of five weather stations to researchers and students. CE SAIN has supported the FLMLA to disseminate and promote weather data use among researchers, lecturers and students. Data will be publicly available and accessed via mobile phone, tablets and computers. The FLMLA will continue to promote this in the state owned universities including UBB, Meanchey, and University of Kampong Cham. These data have made a huge contribution to the quality of research and extension activities in Cambodia.

- Twenty-five unique technologies are being demonstrated in the five ATPs, for a total of 78 technologies across all parks. Eighteen of these technologies are in Phase III of development, meaning that they are ready for scaling. These technologies are accessible throughout the zone of influence of USAID, Kandal province, Kampong Cham province, and at the Royal University of Agriculture in Phnom Penh, attracting 1,536 visitors (661 female, 43%).

- Thirty proposals were awarded to RUA faculty and staff that includes six international grants. These grants have contributed to improving lab facilities and purchase of consumable materials in order to increase lab activities between lecturers and students. MoAs have been signed with USDA, Can Tho University, KSU and Michigan State University.

8. Publications

1. Chay C., et al. (2019). Total phenolic content and antioxidant activity of rice wine from waxy pigmented and non-pigmented rice varieties produced by traditional and multi-parallel fermentation. Food Research 4 (1) : 199 – 206.
2. Chay C., et al. (2018). Quality improvement of traditional rice liquor (srasor) processing in Takeo Province, Cambodia. Food Research 2 (4): 299 – 306.
3. Ket P., et al. (2018). Simulation of Crop Growth and Water-Saving Irrigation Scenarios for Lettuce: A Monsoon-Climate Cast Study in Kampong Chhnang, Cambodia. Water 10 666. https://doi.org/10.3390/w10050666
4. Le K., et al. (2018). Evaluation of the performance of the EPIC model for yield and biomass simulation under conservation systems in Cambodia. Agricultural Systems 166:90-100. https://doi.org/10.1016/j.agsy.2018.08.003
5. Le K., et al. (2018). Evaluation of long-term SOC and crop productivity within conservation systems using GFDL CM2.1 and EPIC. Sustainability 10(8), 2665. http://doi.org/10.3390/su10082665
6. Kiely S., et al. (2019). Perceptions of Risk and Risk Management Strategies: Identifying Alternative Strategies to Promote Smallholder Vegetable Production in Cambodia. International Journal of Agricultural Extension and Rural Development Studies. Vol.6, No.5, pp. 21-43. European Centre for Research Training & Development UK www.eajournals.org
7. Pheap S., et al. (2019). Multi-functional assessment of soil health under Conservation Agriculture in Cambodia. Soil and Tillage Research. Volume 194 - 104349 https://doi.org/10.1016/jstill2019104349.
8. Ritzema R.S., et al. (2019). Household-level drivers of dietary diversity in transitioning agricultural systems: Evidence from the Greater Mekong Subregion. Agricultural Systems. 176 - 102657. Elsevier.
9. Theng D., et al. (2019). Production of fiberboard from rice straw thermomechanical extrudates by thermopressing: influence of fiber morphology, water and lignin content. European journal of wood and wood products. Volume 77 – Issue 1:15-32. Springer Berlin Heidelberg.
10. Edralin D. et al. (2017) Conservation agriculture improves yield and reduces weeding activity in sandy soils of Cambodia. Agronomy Sustainable Development (2017) 37:52 doi 10.1007/s13593-017-0461-7.
11. Hok L., et al. (2018). Enzymes and C pools as indicators of C build up in short-term conservation agriculture in a savanna ecosystem in Cambodia. Soil and Tillage Research 177: 125-133. https://doi.org/10.1016/j.still.2017.11.015
12. Ket P., et al. (2018). Simulation of crop growth and water-saving irrigation scenarios for lettuce: a monsoon-climate case study in Kampong Chhnang, Cambodia. Water 10, 666. https://doi.org/10.3390/w10050666
13. Le K.N., et al. (2018). Evaluation of the performance of the EPIC model for yield and biomass simulation under conservation systems in Cambodia. Agricultural Systems, 166, 90-100. doi: https://doi.org/10.1016/j.agsy.2018.08.003
14. Le K.N., Jha M.K., Jeong J., Gassman P.W., Reyes M.R., Doro L., Hok L. (2018). Evaluation of long-term SOC and crop productivity within conservation systems using GFDL CM2.1 and EPIC. Sustainability 10(8), 2665. doi: https://doi.org/10.3390/su10082665
15. Le K.N., et al. (2018). Evaluating carbon sequestration for conservation agriculture and tillage systems in Cambodia using the EPIC model. Agriculture, Ecosystems & Environment, 251, 37-47. doi: https://doi.org/10.1016/j.agee.2017.09.009

RODS

RODS

Research Output Dissemination Study

1. Lead Institution: University of California, Davis
- U.S. Collaborating Institution:
  - Feed the Future Innovation Labs

2. Research Team:
- Lead Investigator:
  - Nancy Allen

3. Executive Summary

The creation of the 24 Feed the Future Innovation Labs (ILs) drew on the expertise of leading universities to channel research to innovations that address priority challenges of global hunger, poverty and under-nutrition. There is a need across ILs for improved understanding and systematic tracking of outcomes and impacts of IL research investments. Decades of technology adoption studies and impact assessments has produced an abundant literature that documents the complexity of the adoption process and underscores the range of independent variables known to accelerate as well as impede adoption and scaling of innovation. A singular challenge for the Research Output Dissemination Study (RODS) is to simultaneously integrate and advance understanding of this multi- dimensional complexity and simplify it enough to allow evaluation of a broad range of innovations classified in the study as biological, management-cultural, and mechanical-physical.

Bags of "Palau", a cowpea variety created through the Feed the Future Innovation Lab for Collaborative Research on Grain Legumes and distributed through ISRA in Senegal. Photo credit: Chris Pannkuk.

4. Project Goals and Objectives

Overall Goal

The objective of RODS was to gain a better understanding of the dissemination, use and adoption of research outputs from USAID-funded Feed the Future Innovation Labs (ILs) and its predecessor program, Collaborative Research Support Projects (CRSPs). RODS was designed to explore partnership dynamics at the critical juncture at which ILs transfer an innovation to a dissemination entity. The study focused on research outputs after they were transferred to the entities facilitating their dissemination. Dissemination is defined in this study as "active and planned efforts to encourage target groups to adopt an innovation."

A case study approach was chosen as a method well suited to capturing the complex interplay of actors and processes in innovation systems. Case study research was designed to: (a) determine if dissemination of the identified innovations was occurring as reported; (b) gather evidence of use and adoption of new technologies; (c) learn more about scaling efforts and results; and (d) gain a better understanding of how ILs and dissemination entities work together to improve adoption and scaling outcomes. Understanding the process of research output dissemination was guided by an initial set of Key Evaluation Questions:

- Innovation Characteristics: What are the characteristics of the innovation that enable/impede adoption? How well is this understood/knowledge used by the IL and dissemination entities?
- Impact Pathway and Response: What is the impact pathway for this innovation? Was/is this formalized by IL or partner entities? What does this look like on the ground? Level of engagement

through to end-user?
• Dissemination and Scaling Plans: Was/is there a dissemination plan? Is scaling under discussion? What factors were considered? Does this make a difference?
• Enabling Environment Consideration and Response: Was consideration given to challenges of the enabling environment? Was this information used?
• Partnership Engagement: How does IL engage with partners and other stakeholders? How are partners selected? With dissemination clearly in mind? How is it articulated in the focus country?

Overall Objectives

Objective 1: Determine if and how dissemination, use and adoption of a subset of transferred innovations identified in the Research Uptake Study is occurring.

> The RODS team was encouraged to increase attention to scalability of the innovations during the study and additional questions and analysis were later added to assess scaling potential.

Objective 2: Observe how entities working on dissemination, use, and adoption are working through commercial, public and partnership pathways, and engaging with entities ineach of these spheres including the ILs during the dissemination process.

Objective 3: Evaluate the design and implementation of the dissemination plans and relevant enabling environment factors for the innovations according to market analysis techniques as well as scaling theory and practice.

Objective 4: Provide analysis of the current and potential outcomes and impacts of the innovations on the target groups

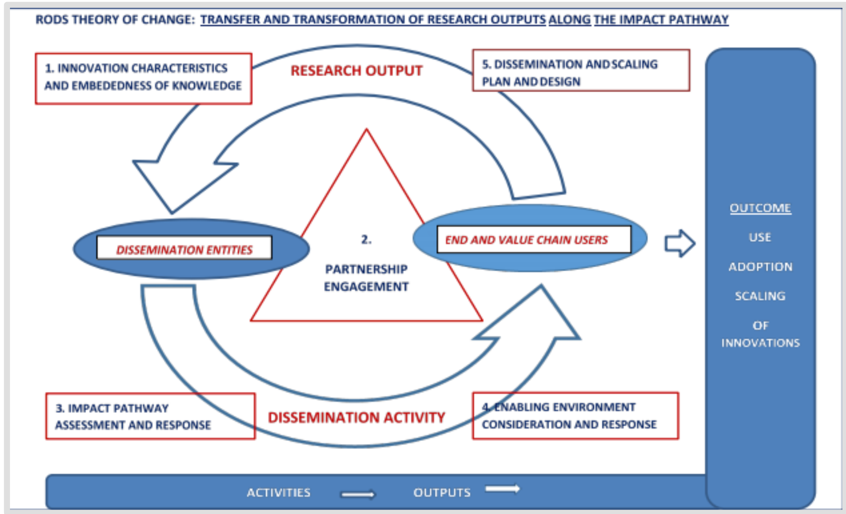
5. Overview of Activities

Overall Approach

Theory of Change

The research team developed a Theory of Change (TOC) informed from an AIS perspective. The TOC upholds the view that the primary role of ILs remains in the research phase and also that technology adoption at an impactful scale, scope, and pace is improved by strong partnership engagement.

The TOC anticipated that research partners and dissemination entities share knowledge and address: (1) next-user and end-user needs, (2) enabling environment constraints, (3) impact pathway relationships, and (4) scaling demands. The use of the TOC framework and associated impact pathway analysis places emphasis on enabling environment context (institutions and polices), the relationships between “users” along the impact pathway and on identifying the capacity building requirements needed to sustain innovation.



The driving principles of this TOC, namely informed partnership and strategic response along the impact pathway, drew heavily on recent efforts from two CGIAR Research Programs, Climate Change, Agriculture, and Food Security (CCAFS) and Agriculture for Nutrition and Health (A4NH).

RODS Study Questions

The TOC was used to generate a series of Key Evaluation Questions (KEQs), which were framed with the goal of better understanding factors critical to dissemination and adoption of innovations.

- **Innovation Characteristics:** What are the characteristics of the innovation that enable/impede adoption? How well is this understood/knowledge used by the IL and dissemination entities? What level of adaptation of innovation is involved and how does this occur?
- **Impact Pathway and Response**: What is the impact pathway for this innovation? Was/is this formalized by IL or partner entities? What does the IL do with this information? What does this look like on the ground? Level of engagement through to end-user?
- **Dissemination and Scaling Plans:** Was/is there a dissemination plan? Is scaling under discussion? What factors were considered? Does this make a difference?
- **Enabling Environment Consideration and Response:** Was consideration given to challenges of the enabling environment? Was this information used?
- **Partnership Engagement:** How does IL engage with partners and other stakeholders? How are partners selected? With dissemination clearly in mind? How is it articulated in the focus country?

The questions above ascribe a role in dissemination and scaling for the Innovation Lab mediated through purposeful partnership engagement.

These KEQs were developed into semi-structured interview protocols with sets of questions specifically designed for IL Directors, principal investigators, dissemination partners, farmers, and other subjects (see Annex A). Each case study was unique with respect to type of innovation, length of time in development, country context and other dimensions. Study questions were adapted extensively in practice to reflect this diversity (See Annex B). Discoveries in the field required a highly dynamic approach to data collection.

Study Design

RODS is part of a three-phase examination of the research outputs and outcomes of Innovation Labs, including: (1) Research Uptake Study; (2) Research Output Dissemination Study and a (3) proposed Impact Analysis.

Research Uptake Study (RUS)

An initial "Research Rack-Up" exercise resulted in a list of more than 1,000 innovations emerging from Feed the Future Innovation Labs. This list included hundreds of hybrid crosses or lines of one or two commodities, only a few of which might ultimately be used to produce a registered new crop variety. This list was winnowed to 502 innovations with more evident readiness for research uptake. Kansas State University's Sustainable Intensification Innovation Lab (SIIL) and the Bureau of Food Security (BFS) then identified 137 innovations in Phase 3 (ready for uptake) across 14 ILs for survey examination. SIIL undertook this Research Uptake Study (RUS), gathering survey responses from 12 of the 24 ILs resulting in the identification of 105 innovations that had been transferred to (or taken up by) named dissemination entities.

Research Output Dissemination Study (RODS)

SIIL, in close consultation with USAID, identified 16 innovations in a Request for Proposals (RFP) for the Research Output Dissemination Study (RODS). The 16 innovations were chosen to be representative of the various innovation categories.

> The RUS report served a number of useful purposes in the classification and distribution of innovations across the following category types: (1) mechanical/physical, (2) biological, (3) management and cultural practices, and (4) multiple/other.

Team Composition for RODS

The RODS traveling team consisted of:

- Dr. Nancy J. Allen, an established international development professional and monitoring, evaluation and learning expert from the University of California, Davis.
- Dr. Chris Pannkuk, a soil scientist and former director for Washington State University's International Research and Development Office.
- Mr. Levi McGarry, agricultural research assistant and communications expert.
- Professor Thomas L. Rost, UC Davis Professor Emeritus of Botany and frequent consultant in the College of Agriculture & Environmental Sciences on international projects. Professor Rost worked with the team on tomato grafting.

The team was advised by Professor Travis Lybbert of the UC Davis Department of Agriculture and Natural Resources Economics.

6. Accomplishments & Utilization of Research Outputs (Country-Level)

1. Completed and submitted the "Research Output Dissemination Study: Examination of Dissemination Pathways in the Use, Adoption, and Scaling of Research Outputs of Feed the Future Innovation Labs" final report of the findings from the field evaluations.

2. Eight cases included in the study have generated innovations that confer both private economic benefits and public environmental benefits, some with good prospects for continued scaling and impact. The selected innovations included in the study were: Conservation Agricultural Practices to Reduce Global Land Degradation (Kenya and Nepal); Breeding Cowpea Varieties for Improved Insect Resistance (Senegal); Drying Beads for Post-Harvest Drying and Storage (Bangladesh); Index-Based

Livestock Insurance (Kenya); High-Efficiency Multi-Purpose Solar Dryer to Decrease Post-Harvest Loss and Increase Crop Quality (Senegal); Low-Cost Hermetic Storage Bags for Long-Term Grain Storage (Bangladesh); Tomato Grafting for Resistance to Soil Borne Diseases (Bangladesh); and Trichoderma as Biocontrol for Soil Borne Pathogens (Nepal).

3. Completing field evaluations in Senegal and Kenya, which provided end-user experiences for four of the innovations under study

4. A growing understanding of how technology transfer pathways are supported by agricultural innovation systems (AIS), and continued acknowledgement of the role of Innovation Labs and university researchers within an AIS

5. Evaluation of surface-level social networks related to dissemination of specific innovations

6. Presenting rough findings to gathered attendees of the Innovation Lab Directors' Meeting, Sept. 11-12, 2018, in Washington, D.C.

7. Challenges and Opportunities

The challenges of transitioning academic innovations from laboratory to end-user are well recognized and have been extensively documented by scientists and development practitioners in the technology transfer literature.

Challenges

Many of those common themes were underscored in these case studies. Some of them are presented here to bring attention to issues where improvements are needed. Others are presented to reinforce the significant investments required to bring research forward for the benefit of the target households in Feed the Future countries.

The following topics deserve more attention in research design:

- **Smallholder Farmers and Purchasing Power.** Although smallholder farmers are the intended target beneficiaries of Feed the Future IL outputs, farmers are often unable to afford the price of the new technologies. Price considerations were a barrier to adoption among smallholder farmers in the case of the **Solar Dryer, Drying Beads,** and **Index Insurance** and to a lesser extent, storage bags and cowpeas. Willingness to pay analysis was conducted rigorously in the case of Index Insurance but additional attention to the topic is critical in the case of the Solar Dryer and important for further scaling of Drying Beads.
- **Champions.** Key individual actors, or 'champions', are often central to disseminating innovations. This was profoundly evident in the case of Index Insurance. Such individuals, through force of will and passion and network placement can be the key factor in increasing adoption efforts, 140 though often their emergence is often fortuitous. Withdrawal of their interest as may be the case in Drying Beads or a particular Cowpea Variety can likewise bring dissemination efforts to a halt. Efforts to identify or support champions deserve attention in dissemination planning
- **Technology Packages.** Few technologies present as singular adoption choices. They are more likely to be disseminated as part of a package. However, some innovations that might be disseminated more effectively as part of a package of both technical elements and organizational

knowledge (e.g., a new crop variety and agronomic guidelines) are not always effectively coordinated. Certain elements of a technology package may diffuse independently and widely, the impact of which is often not tracked or easily measured. Sometimes as in the case of **Storage Bags** bundling a technology with other innovations may deflect necessary attention.

- **Monitoring, Evaluation, and Learning.** In general, we found that ILs rarely track research outputs or continued adaptation once the innovation transfer has taken place. Important lessons about scaling are likely not being captured in all of these cases. On-going MEL is needed. We found strong evidence of uptake by seed companies in the case of ***Drying Beads***. Yet, no system is currently in place to track continuing diffusion in Bangladesh or to garner lessons learned for scaling elsewhere, where the enabling environment may not be as robust as Bangladesh.

The following factors are mentioned to reinforce the challenges of bringing an innovation into productive or profitable use, simply as a reminder that many innovations deserve long-term, broad research and aligned systems investments:

- **Time Intensity.** The time needed to take an innovation through the research and development phase to the dissemination and adoption phases can take a decade, often longer, and may require substantial continuing investment. The foundations for successful introduction of new technology often build on decades of prior investment. For example, the development of a new ***Cowpea*** variety in Senegal is the result of decades of USAID-funded capacity building in plant breeding at ISRA.
- **Systems Investments.** The foundations for successful introduction of a new technology often build on decades of prior systems investments and/or concerted effort to build informed effective demand for the technology. The success of ***Trichoderma*** and ***Tomato grafting*** efforts by IPM IL in Nepal built on years of investment in small-holder vegetable production and more recent investments in agro-vet supply chain investments.
- **Context Dependence.** Each innovation is extremely dependent on the agricultural innovation system and context in which it is deployed, and dissemination success depends greatly on the enabling environment around the innovation. Whether the ***Drying* Beads** success in Bangladesh can be replicated in a country without a robust private vegetable seed sector is unclear. Adapting the delivery mechanism for informal seed sector storage and exchange would require substantial adaptation and systems investments. ***Index-Based Livestock Insurance*** researchers and implementers have learned critical lessons that can be applied to scaling of index insurance in other countries. However, specific aspects of the Kenya case, including the availability and suitability of NDVI data and the technical capacity to devise insurance contracts, contributed to its success. These elements may not exist or transfer directly in another setting and the innovation would require adaptation and associated capacity building.
- **Leveraging Funds.** The ability to leverage additional funds for dissemination activities is instrumental to effective innovation. Bridging the gap between production of research outputs and development of affordable, accessible technology is not only time-intensive but expensive. In a strictly commercial scenario, this gap is funded by interested equity investors. Few, if any, innovations directed at smallholder farmers in Feed the Future countries have garnered substantial equity investment. Public-private partnerships may fill some of that gap, but the need for additional donor funding to explore commercial development or public scaling of products was evident in most of the case studies evaluated. **Index-based Livestock Insurance** has been able to attract substantial funds for product development and dissemination from multiple donors including the Bill & Melinda Gates Foundation, World Bank, DFID, and others. IBLI achieved this by virtue of the novelty and promise of the innovation, published ex-ante impact assessments, pilot project successes, purposeful publication of lessons learned, and dedicated efforts of its champions at ILRI

and leading researchers at UC Davis and Cornell. The IPM IL has been effective at leveraging work on **Trichoderma** with a USAID/Nepal Associate Award.

Opportunities

Some findings emerged from just one case, but seem worthy of further study and reflection. The suggestions below have the potential to improve the dissemination, scaling, and adoption of innovations and the implementation of more effective communication and organization of efforts between ILs and other entities working in Feed the Future countries.

- **Collaboration between IARCs and Innovation Labs.** CGIAR centers, like most ILs, understand their mandate as research not development. ILs and CG centers share some natural affinity as research entities and yet collaboration is rarer than expected. The case of IBLI provides an example of productive CG and IL collaboration benefitting the IL and global research on scaling. CGIAR centers have stronger organizational presence than ILs in Feed the Future countries, which allows them to participate more actively in multi-stakeholder fora as well as policy change efforts to support dissemination. CGIAR centers also offer a substantive amount of local knowledge.
- **Organizational Presence in Feed the Future Countries.** ILs across the case studies have very different organizational arrangements within their focus countries. Some ILs have a regular presence on the ground and fund permanent staff; other ILs pay for a share of an individual's services. Many ILs communicate very regularly with research partners, but otherwise have no incountry operations. The Integrated Pest Management Innovation Lab (IPM IL) maintains offices in both Nepal and Bangladesh at relatively low cost. The greater presence on the ground clearly affords deeper knowledge of enabling environment factors, contributes to on-going capacity building, and forges relationships with bridging partners. This presence may also have created the relationships that help to secure an associate award for their continued work in Nepal.
- **Formal Implementation Research.** The International Livestock Research Institute (ILRI) assumed a lead role in dissemination of IBLI in Kenya and Ethiopia and brought social science rigor to the analysis of that effort. For 10 years, the IBLI team of social scientists and geospatial analysts has engaged in rigorous and transparent implementation research. In so doing, they contributed to product improvement and the generation of knowledge for related innovations in collaboration 142 with the Assets and Market Access IL (AMA IL). This level of active engagement in dissemination and product development by a CGIAR center, though not believed to be common, appears productive in this instance.

Sustainable Intensification Assessment Framework

Developing Indicators for Sustainable Intensification (SI)

1. Lead Institution: University of Florida & Michigan State University

2. Research Team:

- Lead Investigators:
  - Cheryl Palm
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  - Mark Musumba

3. Executive Summary

The goal of this project is to develop and recommend indicators and metrics for the Sustainable Intensification (SI) of agriculture within a framework of domains using three scales: field level, farm or household level and landscape level. This project will evaluate SI indicators and metrics, assess robustness and sensitivity of indicators, conduct data gap analysis by various groups involved in the SI indicator work, refine the SI indicators and metrics for their usefulness and develop a further framework for understanding and optimizing SI trade-offs for presentation to stakeholders. The project will continue some of the work put forth by Africa RISING.

4. Project Goals, Activites & Mode of Measurement:

Overall Goal

The primary purpose of the Sustainable Intensification Assessment Framework is to strengthen researchers' ability to holistically assess the performance of an innovation in terms of the direct and indirect consequences within and across domains.

> The framework is primarily intended to guide agricultural scientists working in research for development but is flexible and can be used by scientists interested in sustainable intensification more broadly.

Scientists may use this framework for a pre-adoption assessment of the potential sustainability of their innovation. This pre-adoption assessment provides important information for use in the adoption phase (roll out or scale up phase) of the innovation. The framework of indicators and metrics provided below includes both 'gold standard' approaches, as well as, simplified methods and metrics as options that may be more feasible to use considering the spatial, temporal, and cost limitations. From these tables of indicators researchers and stakeholders can select those most relevant to their programs.

This indicator framework can be used to analyze the relative sustainability of innovations for intensification by collecting data for the most relevant indicators for an innovation and comparing them with the status quo. The status quo is often some form of practice common in the same location. It is important to have a fair comparison so that potential benefits of the innovation are not overstated. In some cases, multiple comparisons may be needed. For example, in section 3.5.1 we summarize a study (Snapp et al., submitted) where the relative sustainability of intercropped and fertilized maize and legumes is compared to both unfertilized sole maize (the most common farmer practice) and fertilized sole maize (another farmer practice that aids in distinguishing the effect of the legumes from the effect of the fertilizer). Where long-term data is available, the SI indicators framework can also be used to quantify trajectories of sustainable intensification by comparing indicators from all domains across time.

Data on SI indicators can be presented through visualization techniques, such as radar charts to compare performance of innovations. Instead of combining indicators into an index (where important details become obscured), we recommend presenting the results for each indicator separately. This allows communities, scientists, implementation partners, and policy makers to objectively evaluate the research results based on the importance they assign to each indicator. Different stakeholder groups may have different priorities regarding sustainability related goals (e.g., biodiversity conservation, agricultural production, food security, and gender equity). There is a growing move towards developing composite indicators for each sustainability pillar or domain and for all domains (Gómez-Limón and Sanchez-Fernandez, 2010; Haileslassie et al., 2016). Although such composite indices can be estimated using this framework, we believe that estimating and presenting individual indicator to stakeholders provides a transparency and parsimony to identifying change and performance.

A critical component of this assessment is to identify potential tradeoffs and synergies from an SI intervention. In the exercise provided in Section 3.2, researchers can consider how the various indicators listed under each domain might be affected positively or negatively by an intervention that they are investigating or planning to research. This exercise provides a structured means of considering the broader farming and livelihood systems and selecting the indicators that reflect these potential tradeoffs and synergies. This type of qualitative assessment should be informed 7 by the scientific literature as well as by discussions with farmers, fellow researchers, NGOs or other stakeholders about the potential direct and indirect effects of a SI innovation. By using this exercise, researchers can anticipate potential synergies and tradeoffs and minimize unintended negative consequences by mitigating them through the research design and implementation.

The SI indicators framework can also be used to guide monitoring and evaluation (M&E) efforts in development projects. All of the key concepts and methods for measuring or estimating the indicators are presented in this framework and the accompanying manual of SI indicators. Several considerations are needed to effectively scale up or aggregate plot and household level indicators to assess the project-level effect (such as at the village, watershed, or sub-district level [Marinus et al., forthcoming]). Nevertheless, the same process for selecting the most relevant indicators and reflecting on synergies and tradeoffs can be applied to M&E for development projects.

Overall Approach

Sustainable Intensification (SI) offers a means to balance the environmental, economic, and social objectives of agriculture. Agricultural intensification may be defined as increasing output per unit input per unit time. A narrow definition of sustainable intensification is "production of more food on the same piece of land while reducing the negative environmental impacts and at the same time increasing the contributions to natural capital and flow of environmental services" (Zurek et al., 2015). The definition of SI has evolved to include non-environmental dimensions such as social issues, economics, and the human condition (Loos et al., 2014). The inclusion of social aspects helps ensure a balanced approach to the intensification process. In this guide, we present a framework of objective-oriented SI indicators organized into five domains critical for sustainability: productivity, economic, environment, human condition, and social domains. The objective-oriented indicator assessment is similar to the goal-oriented framework proposed by Olsson et al. (2009) in which objectives of the innovation are identified and then indicators are linked to the objectives to assess performance in a balanced approach across domains. The metrics for each indicator are categorized across spatial scales: field, farm, household, and landscape, so that the assessment can be used for innovations at any scale and so that cross-scale linkages can be considered (Figure 1).

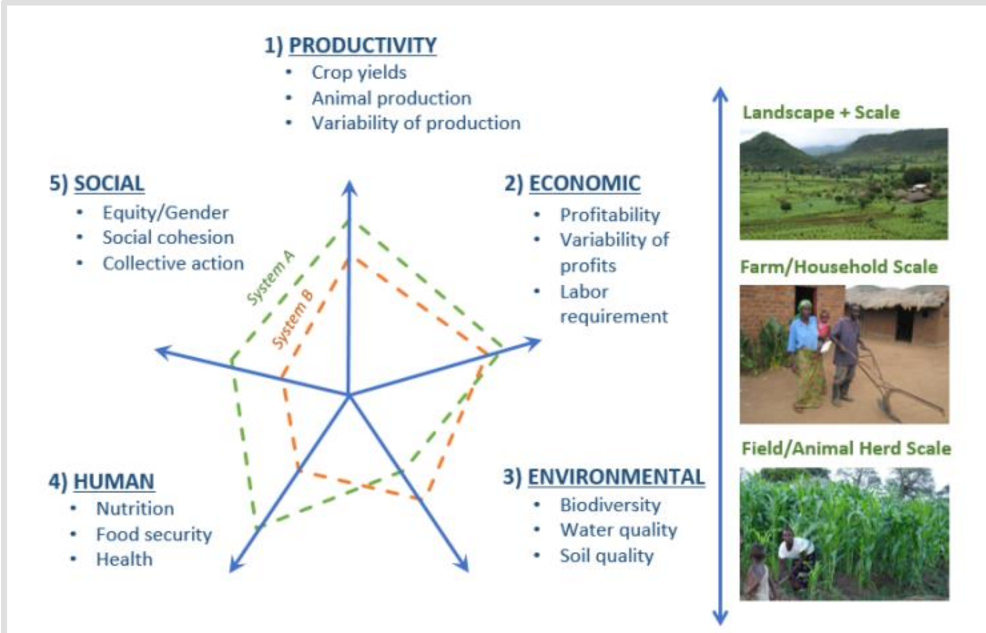

Figure 1: Interlinkages across the five domains of sustainable intensification and across spatial scales with examples of indicators for each domain.

The framework was developed to provide indicators for assessing the relative sustainability of an innovation across the five domains. Our target audience is researchers involved in developing and analyzing innovations for SI, particularly in the research for development context. The framework was developed primarily for use in smallholder farming contexts where changes in agricultural production can have positive or negative effects on development 4 goals such as alleviating poverty, avoiding land degradation, increasing food security and nutrition security, and supporting women's empowerment (Figure 2).

To develop innovations that can support these diverse goals, research to assess SI innovations needs to be interdisciplinary, drawing upon the theories and methods of the biophysical and social sciences. Ideally, this framework will support assessment of sustainable agriculture intensification innovations through interdisciplinary, iterative co-learning approaches. The framework is not designed for project evaluation, though it can contribute towards that goal.

Mode of Measurement

The five domains of sustainable intensification, which emerged during discussion by stakeholders in a meeting in Accra, Ghana, in 2013, are productivity, economic, environment, human condition and social domains (Glover, 2016). This framework of five domains distinguishes important aspects of sustainable intensification compared to the three domains used by many sustainability assessments: economic, environmental, and social domains (Lopez-Ridaura et al., 2002; Van Cauwenbergh et al., 2007). We are aware that there is overlap among the indicators in the different domains and these overlaps indeed provide additional insights. For our purpose, the domains are described and organized as follows:

> The five-domain framework ensures that important aspects such as equity (gender, age, class), nutrition and community factors such as social cohesion and collective action are not overlooked in the indicators selection process.

Productivity: The productivity domain is critical in capturing productivity both in cropping and livestock systems. Following the SI literature, this domain focuses on land as a critical input. Increasing productivity is the essential characteristic of intensification, with the goal of increasing output per unit of input for a given time period (season or year). In livestock systems, stocking rates or offtake may be used as a measure of intensification, while in cropping systems intensification focuses on yields (Mahon et al., 2017). This domain also captures postharvest losses and cropping intensity (the number of crops per year from the same piece of land). It also contains indicators that may be used to assess the production potential of the land as well as, potential variability due to biophysical aspects. Other inputs associated with intensification (such as labor, water quality, fertilizer, and capital) are captured in the economic domain.

Economic: This domain focuses on issues directly related to the profitability of agricultural activities and returns to factors of production (land, labor, and capital). In addition to profitability, this domain includes indicators related to the productivity of inputs, apart from land, and includes water, nutrients, labor, and capital. Furthermore, indicators likely to affect the probability of investment in enhancing productivity (market participation) are included. Farmers' decisions to choose which crop to grow and how to allocate resources to different activities are affected by marketability of a given commodity and livelihood strategies chosen to improve wellbeing. This domain captures farmers' market orientation, diversification of income sources, and extent and movement towards high value crop production.

Environment: This domain focuses on the natural resource base supporting agriculture (e.g., soil, water, air), the environmental services directly affected by agricultural practices (e.g., habitat, soil water holding capacity, biodiversity) and the level of pollution coming from agriculture (pesticides, eutrophication, greenhouse gases). Improved efficiency metrics are described under the economic domain but are also critical for tightening nutrient and energy cycles, a key principle for sustainable agriculture.

Human condition: This domain contains indicators related to the individual or household, including nutrition status, food security, and capacity to learn and adapt. While some of these concepts are dependent on social interactions (such as within the household or community), they are distinct from those in the social domain that directly focus on interpersonal relationships. 8

Social: This domain focuses on social interactions of the farming communities or society, including equitable relationships across gender, equitable relationships across social groups, the level of collective action, and the ability to resolve conflicts related to agriculture and natural resource management.

5. Launch of Online Web Version of the SI Assesment Framework

The Sustainable Intensification (SI) Assessment Framework web tool was developed at the beginning of FY 2019. The purpose of the web tool is to facilitate greater access and usability of the framework for the SI research community. The tool was showcased at several venues, including the American Society of Agronomy and Crop Science Society of America Annual Meeting in November 2018, and the SIIL Annual Meeting in April 2019. The SI Assessment Framework is being utilized by all SIIL projects to quantify synergies and tradeoffs of their technologies across the five domains (productivity, economic, environment, human, and social condition). These efforts will continue to be encouraged to further investigate the utility of the tool in assessing farming systems.

Appendix A – SIIL Acknowledged ME Publications

PEER REVIEWED JOURNAL ARTICLES

1. Araya A., Gowda P.H., Golden B., Foster A.J., Aguilar J., Currie R., Ciampitti I.A., Prasad P.V.V. 2019. Economic value and water productivity of major irrigated crops in the Ogallala aquifer region. Agricultural Water Management 214: 55-63.
2. Araya A., Kisekka I., Gowda P.H., Prasad P.V.V. 2018. Grain sorghum production functions under different irrigation capacities. Agricultural Water Management 203: 261-271.
3. Araya A., Kisekka I., Prasad P.V.V., Gowda P.H. 2017. Evaluating optimum limited water management strategies for corn using crop simulation models. ASCE Irrigation and Drainage Engineering 143 (10): 04017041.
4. Araya A., Kisekka I., Xin L., Prasad P.V.V., Gowda P.H., Rice C.W., Andales A. 2017. Evaluating the impact of climate change on irrigated maize production in Kansas. Climate Risk Management 17: 139-154.
5. Araya A., Prasad P.V.V., Gowda P.H., Afewerk A., Abadi B., Foster A.J. 2019. Modeling irrigation and nitrogen management of wheat in northern Ethiopia. Agricultural Water Management 216: 264-272.
6. Araya A., Prasad P.V.V, Gowda P.H., Djanaguiraman M., Kassa A.H. 2020. Potential impacts of climate change factors and agronomic adaptation strategies on wheat yields in central highlands of Ethiopia. Climatic Change 159: 461-479.
7. Araya A., Prasad P.V.V., Gowda P.H., Kisekka I., Foster A.J. 2019. Yield and water productivity of winter wheat under various irrigation capacities. Journal of American Water Resources Association 55: 24-37.
8. Araya A., Prasad P.V.V., Zambreski Z., Gowda P.H., Ciampitti I.A., Assefa Y., Girma A. 2020. Spatial analysis of the impact of climate factors and adaptation strategies on productivity of wheat in Ethiopia. Science of Total Environment 731: 139094.
9. Djanaguiraman M., Belliraj N., Bossmann S., Prasad P.V.V. 2018. High temperature stress alleviation by selenium nanoparticles treatment in grain sorghum. ACS Omega 3: 2479-2491.
10. Djanaguiraman M., Nair R., Giraldo J.P., Prasad P.V.V. 2018. Cerium oxide nanoparticles decrease drought induced oxidative damage in sorghum leading to higher photosynthesis and grain yield. ACS Omega 3: 14406-14416.
11. Djanaguiraman M., Narayanan S., Erdayani E., Prasad P.V.V. 2020. Effect of high temperature stress during anthesis and grain filling periods on photosynthesis, lipids and grain yield in wheat. BMC Plant Biology 20: 268.
12. Djanaguiraman M., Perumal R., Ciampitti I.A., Gupta S.K., Prasad P.V.V. 2018. Quantifying pearl millet response to high temperature stress: thresholds, sensitive stages, genetic variability and relative sensitivity of pollen and pistil. Plant Cell and Environment 41: 993-1007.
13. Djanaguiraman M., Perumal R., Jagadish S.V.K., Ciampitti I.A., Welti R., Prasad P.V.V. 2018. Sensitivity of sorghum pollen and pistil to high temperature stress. Plant Cell and Environment 41: 1065-1082.
14. Djanaguiraman M., Prasad P.V.V., Kumari J., Rengel Z. 2019. Root length and root lipid composition contribute to drought tolerance of winter and spring wheat. Plant and Soil 439: 57-73.
15. Djanaguiraman M., Prasad P.V.V., Stewart Z.P., Perumal R., Min D., Djalovic I., Ciampitti I.A. 2018. Agroclimatology of oats, barley, and minor millets. In: Agroclimatology: Linking Agriculture to Climate (Eds. J. Hatfield, M. Sivakumar, J. Prueger). American Society of Agronomy. Monograph 60, Madison, Wisconsin, US.
16. Djanaguiraman M., Schapaugh W.T., Fritschi F.B., Nguyen H.T., Prasad P.V.V. 2019. Reproductive success of soybean (Glycine max (L.) Merril) cultivars and exotic lines under high daytime temperature. Plant Cell and Environment 42: 321-336.

17. Faye A., Stewart Z.P., Ndungu-Magiroi K., Diouf M., Ndoye I., Diope T., Dalpe Y., Prasad P.V.V., Lisueur D. 2020. Testing commercial inoculants to enhance P uptake and grain yield of promiscuous soybean in Kenya. Sustainability 12: 3803.
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22. Middendorf B.J., Prasad P.V.V., Pierzynski G.M. 2020. Setting research priorities for tackling climate change. Journal of Experimental Botany 71: 480-489.
23. Naab J.B., Mahama G.Y., Yahaya I., Prasad P.V.V. 2017. Conservation agriculture improves soil quality, crop yield and incomes of smallholder farmers in North Western Ghana. Frontiers in Plant Sciences 8: 996.
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25. Opole R.A., Prasad P.V.V., Djanaguiraman M., Vimala K., Kirkham M.B., Upadhyaya HD. 2018. Thresholds, sensitive stages and genetic variability of finger millet to high temperature stress. Journal of Agronomy and Crop Science 204: 477-492.
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27. Prasad P.V.V., Bheemanahalli R., Jagadish S.V.K. 2017. Field crops and the fear of heat stress – opportunities, challenges and future directions. Field Crops Research 200: 114-121.
28. Prasad P.V.V., Djanaguiraman M., Perumal R., Ciampitti I.A. 2015. Impact of high temperature stress on floret fertility and individual grain weight of grain sorghum: sensitive stages and thresholds for temperature and duration. Frontiers in Plant Science 6: 820 (doi: 10.3389/fpls.2015.00820).
29. Prasad P.V.V., Djanaguiraman M., Stewart Z.P., Ciampitti I.A. 2018. Agroclimatology of maize, sorghum, and pearl millet. In: Agroclimatology: Linking Agriculture to Climate (Eds. J. Hatfield, M. Sivakumar, J. Prueger). *American Society of Agronomy*. Monograph 60, Madison, Wisconsin, US.
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Appendix B – List of SIIL-Supported Technologies and Practices

Phase 1

- Integrating remote sensing-based crop suitability mapping with crop model simulations using APSIM to assess yields and soil health benefits of diversified cropping systems (Precision Agriculture for Smallholder Systems in Africa, Malawi)
- Power-Tiller Seeder prototype for rice paddies in Cambodia with reduced water requirements ASMC, Cambodia)

Phase 2

- Animal-drawn row crop cultivator developed to remove weeds and reduce in-field competition (ASMC, Burkina Faso)
- Animal-drawn single row planter, manufactured locally, to lessen women's drudgery, time and labor during planting season (ASMC, Burkina Faso)
- Bean seed treatment (APRON STAR 42 WS), an innovative crop management practice produced in conjunction with CIAT (Raising Crop Response, Tanzania)
- Conservation ripper designed to till, level and firm soil in a way that was less impactful than plowing an entire field (ASMC, Burkina Faso)
- The Majipump, a solar-powered water lifting mechanism designed for ease of operation, lower weight and little to no operating costs (ASMC, Ethiopia)
- Dual-purpose pearl millet varieties (SL 28, SL 169, SL 423) whose leaves maintain greenness

after grain maturity and had higher grain yields (Dual-Purpose Millet, Senegal)

- Engine-driven maize sheller, developed in conjunction with local farmers and produced locally, to increase shelling and cleaning efficiency, reduce shatter-loss and be gender-compatible (ASMC, Ethiopia)

- Lablab varieties produced to increase both grain and fodder yields (Raising Crop Response, Tanzania)

- Mini-combine rice harvester (4LBZ-110) introduced in Bangladesh, reduced costs by 59% over a traditional rice harvester and represented a 65% reduction in labor (ASMC, Bangladesh)

- Multi-crop versatile seed broadcaster, which can be mounted on a variety of vehicles (motorbike, tractor, power-tiller, etc.), and produced locally (ASMC, Cambodia)

- Cultural practices to improve nitrogen sources for dual-purpose millet, including composting and intercropping with legumes (Dual-Purpose Millet, Senegal)

- Refined yoke, locally produced, for traction animals to reduce burden on them and increase productivity by allowing the animals to work more efficiently (ASMC, Burkina Faso)

- Rice reaper (VR-120), uses an improved design that is less costly to end-users, and was tested and approved by both male and female farmers, local service providers, mechanics and field-level extension workers (ASMC, Bangladesh)

- Digital technology to track malaria hotspots by mapping mosquito breeding suitability (Precision Agriculture for Smallholder Systems in Africa, Malawi)

- Tractor-pulled direct seeder, capable of being pulled by a 4-wheeled tractor, was designed to be able to plant in no-till, dry-land condition (ASMC, Cambodia)

- Two-wheeled tractor-pulled roller-crimper helps improve the overall efficiency of a cropping system by reducing the number of passes needed to mow down cover crop and sow main crops through resulting mulch (ASMC, Cambodia)

Phase 3

- Green manure cover and relay cropping after rice harvest to improve soil fertility, provide a source for animal fodder, and produce seed for cover crops (WAgN, Cambodia)

- Resilient cropping patterns for the polder ecosystems, including the introduction of short-duration, high-yield rice during the wet season and high-yield maize and sunflower during the dry season, to increase yields and income (Unlocking the Production Potential of Polder Communities, Bangladesh)

- Rice transplanter, a walk-behind mechanized tool designed to save time, labor and money over manual transplanting (ASMC, Bangladesh)

- Wild Gardens, a project that focused on how to integrate indigenous food plants into home gardens, while training on their potential nutritional, economic and gender impacts (WAgN, Cambodia)

Phase 4

- Spatial data outlier detection system and MODIS product version comparison applications for Google Earth Engine to allow modelers and other users to minimize error and uncertainty in remote sensing data products used in all agronomic modeling systems (Precision Agriculture for Smallholder Systems in Africa, Malawi)

- Tomatoes grafted onto local eggplant rootstock to produce marketable fruit during the rainy season in Cambodia (non-grafted tomatoes almost always succumb to flooding, waterlogged soils, etc.) (WAgN, Cambodia)

- Visualizing inconsistencies among global agriculture products using Google Earth Engine to aid in identifying where more research might be needed regarding agricultural land classifications and global-scale data (Precision Agriculture for Smallholder Systems, Malawi)

- Web-based, open-access GIS for spatio-temporal crop climate niche mapping used to map climate niches across geographies and temporal scales (Precision Agriculture for Smallholder Systems, Malawi)

2020



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