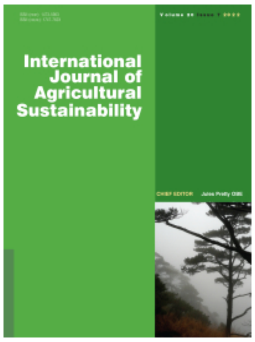

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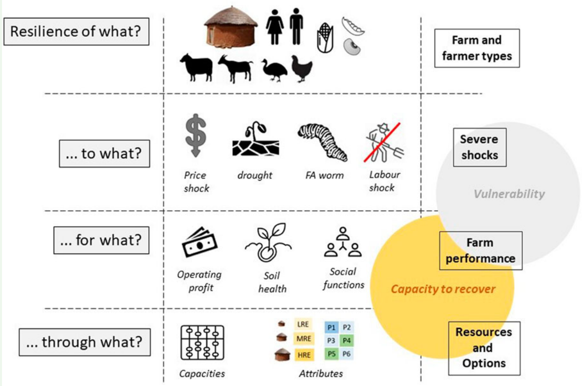
Preparing for, coping with and bouncing back after shocks. A nuanced resilience assessment for smallholder farms and farmers in Northern Ghana

Mirja Michalscheck[a,b], Fred Kizito[c,d,e], Bekele H. Kotu[c], Franklin K. Avornyo[d], Carl Timler[a] and Jeroen C. J. Groot[a,f,g]

[a]Farming Systems Ecology Group, Wageningen University & Research, Wageningen, The Netherlands; [b]International Water Management Institute – West Africa Office, Accra, Ghana; [c]International Institute of Tropical Agriculture (IITA), Tamale, Ghana; [d]International Center for Tropical Agriculture (CIAT), Nairobi, Kenya; [e]Council for Scientific and Industrial Research - Animal Research Institute (CSIR-ARI), Tamale, Ghana; [f]International Maize and Wheat Improvement Center (CIMMYT), Sustainable Intensification Program, Texcoco, Mexico; [g]Bioversity International, Maccarese (Fiumicino), Italy

ABSTRACT

Smallholder farmers in Northern Ghana regularly face shocks, challenging the sustainability of their farms and livelihoods. Different farm households and household members may be differently affected and respond with different coping strategies. We combined whole-farm modelling and farmer consultations to investigate the vulnerability, buffer and adaptive capacity of three farm types in Northern Ghana towards severe climate, economic and social shocks. We further assessed intra-household differences in respective risk mitigation and coping strategies. Our model results indicate that the drought shock would most severely affect all farm types, drastically reducing their operating profits and soil organic matter balance. The medium resource endowed farm was most affected by shocks, but all farm types could enhance their capacity to recover by adopting technology packages for sustainable intensification. Gendered coping strategies included livestock sales, post-harvest storage, activating social networks, rice processing and the collection, processing and sales of wild nuts and fruits. Farmers reported to aim at becoming more resilient by increasing their herd size and expanding their farmland, thereby risking to increase rather than reduce the pressure on natural resources. New questions arise concerning the carrying capacity of local ecosystems and resilience at community and landscape level.



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CONTACT Mirja Michalscheck mirja.michalscheck@gmail.com, Farming Systems Ecology Group, Wageningen University & Research, P.O. Box 430, Wageningen 6700 AK, The Netherlands; International Water Management Institute – West Africa Office, PMB CT 112, Cantonments, Accra, Ghana

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1. Introduction

Building sustainable and resilient food production systems worldwide is one of today's greatest challenges (Cui et al., 2018; FAO, 2015): while global food demand is projected to double between 2005 and 2050 (Tilman et al., 2011), climate change increases production-related uncertainties (IPCC, 2014) and fertile agricultural lands diminish (Abass et al., 2018; Bren d'Amour et al., 2017; IPCC, 2019; Lambin & Meyfroidt, 2011; Montanarella et al., 2016). Visions for multi-functional, circular and biodiverse agricultural production systems that provide equitable and food secure livelihoods (Chaplin-Kramer et al., 2023) need to consider how agricultural systems cope with shocks. Globally, most agricultural systems are exposed and vulnerable to shocks like infestations of crops by pests, disturbances caused by extreme weather conditions, market price fluctuations and labour shortages (Barbier et al., 2009; Birthal & Hazrana, 2019; Groot et al., 2016; Urruty et al., 2016). Smallholders, constituting about 83% of all farm systems globally (Lowder et al., 2016), have been described as particularly vulnerable to shocks due to their high dependency on agriculture for food and income as well as their limited access to formal safety nets (Harvey et al., 2018, 2014; Mashizha, 2019; Muthelo et al., 2019). Previous publications have described the vulnerability to shocks, coping strategies and/or resilience of smallholder farmers (Akponikpè et al., 2011; Barbier et al., 2009; Ghimire et al., 2010; Mertz et al., 2009; Nicod et al., 2020), repeatedly describing women as particularly vulnerable to shocks like droughts and floods and as adopting different coping strategies than men (Assan et al., 2018; FAO, 2018; Magombeyi & Taigbenu, 2008). Factors such as household resource endowment and gendered differences in production have been described as important discriminants for farm management practices and farmers` rooms to manoeuvre (Kuivanen et al., 2016a, 2016b; Michalscheck et al., 2019, 2018; Timler et al., 2017). However, little attention has been paid jointly to site-specific intra- and inter-household differences in resilience. Our main research question is thus whether and how different farm households (farm types) and household members (farmer types) evince different vulnerabilities, coping strategies and pathways of recovery from shocks. Concretely we ask: what are the main shocks affecting farms and farmers at a particular location, how do particular shock scenarios affect them and how are they able to recover with versus without particular sets of good agricultural practices.

In this study, we build on existing work on farm and farmer diversity in Duko, Northern Ghana, to systematically investigate and describe intra- and inter-household differences in terms of the vulnerability to prevalent shocks. We then continue investigating whether local farms and farmers have different strategies and capacities to recover with and without adopting project-proposed technologies for sustainable agricultural intensification. We thus differentiate between the buffer (without new technologies) and adaptive (with new technologies) capacity of farm households (Groot et al., 2016). We acknowledge that farmers deliberately prepare for and attempt to reduce risk, i.e. their transformative capacity (Arnall, 2015). We assess the vulnerability and coping strategies under four severe shock scenarios: a drought, a fall army worm (FAW) infestation, a decline in product price, and a reduction in labour availability. The selection and definition of shock scenarios were based on a participatory assessment and literature review (cf. 3.4 and 3.6). We built upon an existing farm and farmer typology (Michalscheck et al., 2018) to determine differences in the shock-specific vulnerability and coping strategies of different farms and farmers. We furthermore explored differences in their ability to recover, comparing scenarios with and without the adoption of technologies and techniques for sustainable intensification (SI) (Groot et al., 2016) at farm-household level. We used the whole-farm model FarmDESIGN as well as systematic farmer consultations to determine the impact as well as coping strategies per shock. We hypothesized that the general resilience of a farm household increases together with the household's resource endowment and that farm systems become more resilient through the adoption of SI technologies and techniques.

In this manuscript, we first provide a brief overview of our conceptual framework, followed by the methods section, introducing the case study site, describing the local farm types, the SI-technology packages and the shock scenarios. We then explain the general functionality and specific use of the whole-farm model FarmDESIGN as well as the design and implementation of the participatory assessment. Finally, we present and discuss our results, their transferability and the implications for technology-scaling efforts of local research for development projects.

2. Conceptual framework

Sustainable farming systems provide food and income as well as soil health and other ecosystem functions (Dahlin & Rusinamhodzi, 2019). They need to maintain their functions over time and in the face of shocks or stresses, i.e. farming systems need to be resilient. Their resilience, according to Meuwissen et al. (2019), can be described by defining the resilience of what (type of farming system), to what (shocks), for what (functions), with what resilience capacities and attributes. With resilience capacities, the authors (Meuwissen et al., 2019) refer to the systems' robustness, adaptability and transformability. Robustness is defined as the capacity to withstand stresses and shocks (Meuwissen et al., 2019; Walker, 2020). Adaptability is the capacity to alter management decisions (e.g. on inputs, production or marketing) without implementing structural or other fundamental changes to the farm system (Meuwissen et al., 2019). Transformability refers to the capacity to significantly change the structure and feedback mechanisms of the farm system in response to severe shocks or enduring stress (Meuwissen et al., 2019). The resilience capacities are thus an expression of a farming systems' conservation- versus reorganization-options to attenuate or to react to a shock (Ansah et al., 2019; Béné et al., 2012; Meuwissen et al., 2019). With resilience attributes Meuwissen et al. (2019) refer to features that enhance resilience, such as diversity, openness, tightness of feedbacks, system reserves or modularity. Building on work by Jentoft et al. (2007), Biggs et al. (2012) distinguish between the (farming) systems' properties, and the governance system attributes that enhance resilience.

We build on the conceptual elements of Meuwissen et al. (2019) and cluster the two latter ones (capacities and attributes) into the description of resilience 'through what' i.e. we ask what are the features and strategies by different farms and farmers to prepare for, cope with and recover from shocks. In line with Darnhofer et al. (2010), we define a shock as a severe and unexpected or sudden perturbation, differing from permanent challenges or steadily increasing pressures to a farm's performance. We further define vulnerability as the shock-related setback a farming system experiences in its functions and respective performance indicators. A low or no setback in performance after shock would indicate a high respective robustness or adaptability. After a shock, to analyse the recovery, we differentiate between the buffer and adaptive capacity of a farming system (Groot et al., 2016). The buffer capacity refers to a scenario where a farm household uses and re-arranges the current farm components (crop and livestock types and management practices), while the adaptive capacity refers to a scenario where a household can source from additional components (technology packages for sustainable intensification). Within this framework, we thus investigate, whether and in how far the SI-technology packages constitute important resilience attributes for the different farm types and whether they strengthen their resilience capacities. Figure 1 summarizes our conceptual framework.

3. Materials and methods

3.1. Overview of methods

To achieve a nuanced resilience assessment, we built on previous insights on local farm and farmer diversity as well as on local agronomic-trial data (Sections 3.3.2–3.3.2). We then combined own community and expert consultations (Section 3.5), with local definitions of severe shocks (Section 3.6) and quantitative whole-farm modelling (Section 3.7). In line with the UN FAO (2012), we operationalized the resilience concept by capturing changes in farm performance, both during and after shock. During a shock year, we captured the vulnerability of a farming system as the percentual setback in its performance indicators. After a shock, we used the model to explore options for farm-performance oriented, structural re-arrangements for recovery per farm type. We measured a farming systems ability to recover by its improvements in the performance indicators in comparison to the shocked and the original (baseline) state. Our insights into local resilience capacities and attributes were complemented by qualitative farmer reports on coping strategies adopted at the individual-level to buffer food and income shocks.

3.2. Case study site

This study was conducted in Duko (9.56° N–0.83° W), a Dagomba farm community situated north of the regional capital Tamale in the Northern Region of Ghana, see Figure 2. This area is part of the Guinea Savannah agro-ecological zone with a unimodal rainfall regime and an annual precipitation of 1000–1200 mm (FAO, 2005). Farm systems in Duko are rainfed, mixed crop-livestock systems: farmers grow

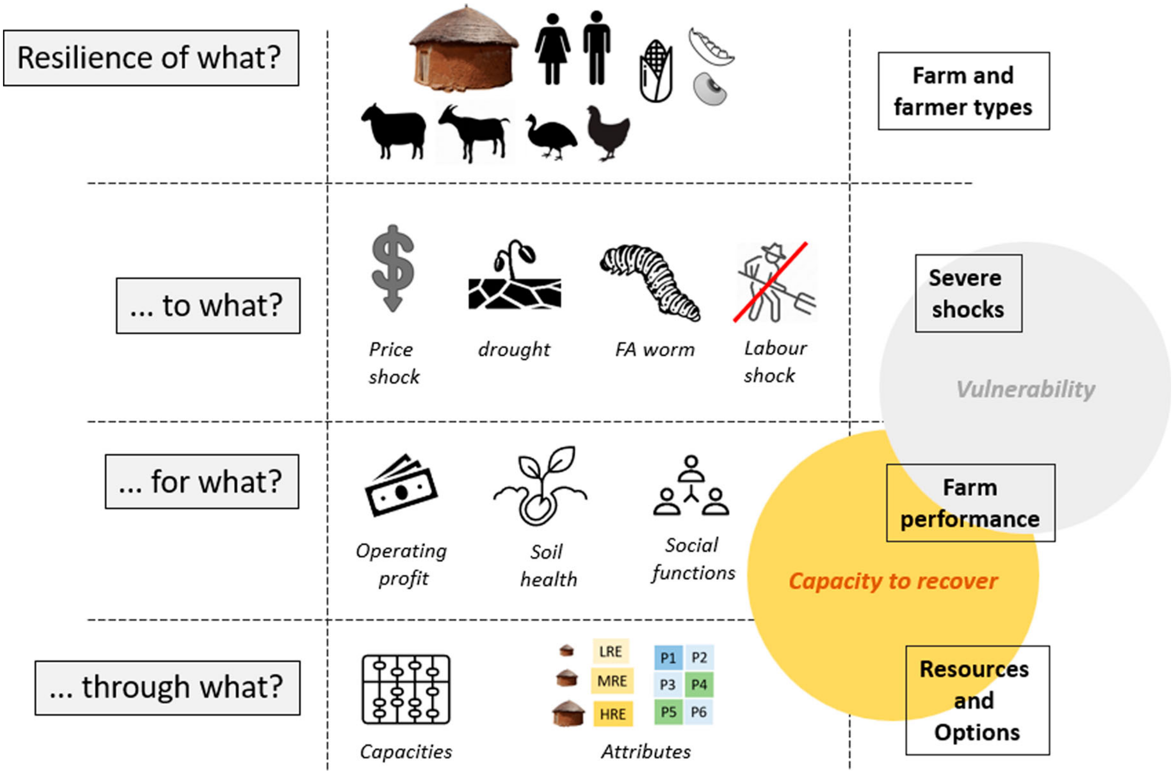


Figure 1. Resilience assessment framework, adapted from Meuwissen et al. (2019).

cereals (maize, rice, millet), tubers (yam, cassava, sweet potato), legumes (cowpea, soybean, groundnut, bambara bean) as well as dry season vegetables (tomato, okra, onion, chili pepper, green leafy vegetables). Depending on their resource endowment, farmers in Duko also own cattle, donkeys, small ruminants and poultry. Farm households retain a portion of their produce for their own consumption and sell the remainder. Duko hosts about 54 large, male-headed and polygamous households, predominantly adhering to Muslim religion. Depending on their gender, household members engage in farming, trading or off-farm activities: household heads are typically responsible for the households' food security, growing staple crops such as maize and yam. The wives are commonly responsible for providing a nutritionally diverse diet to the household. For this purpose they grow soup ingredients like groundnuts and vegetables (Apusigah, 2009; Padmanabhan, 2007). Despite their agricultural activities, women in Duko are described as traders rather than farmers; they buy, process and sell produce in order to make an extra income e.g. to cover the children's basic school fees (Mohammed, 2015). If a household has sufficient land and labour available, adult sons may cultivate own plots, growing cash crops like rice or cowpea to pay for higher education or marriage (I. B. Mohammed, personal communication, 2016).

In the decade 2010–2020 farmers in Duko have been affected by various severe droughts (2010, 2011 and 2019: severe yield loss), severe price shocks (i.a. 2019, rice, −60% of previous market value) and crop pests (FAW infestation since 2017). Farmers also repeatedly report labour shortfalls due to illness, death or out-migration. The recent Covid-19 pandemic constitutes another severe health and economic shock that was not yet recorded in the surveys underlying this study. Despite common features and structures, the farm households of Duko may be grouped into different farm types.

3.3. Farm typology

While in East, Central and Southern Africa farming systems can broadly be characterized as maize mixed farming systems, the West African Savannah systems

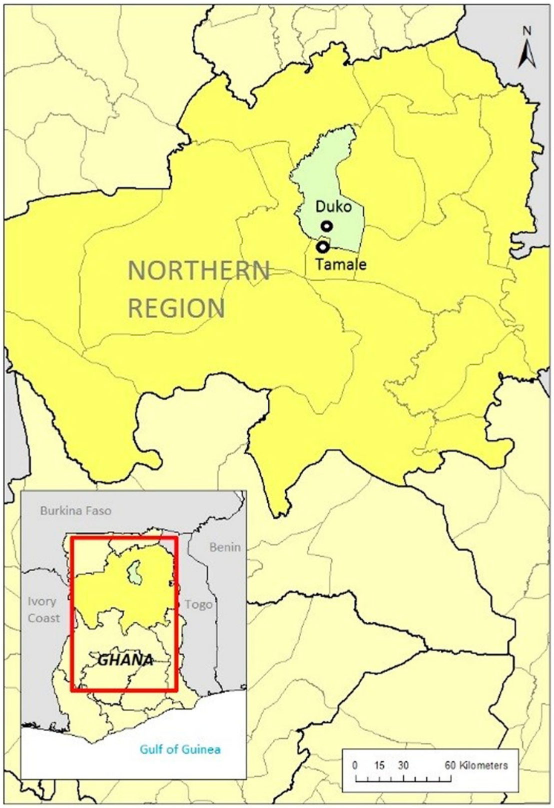


Figure 2. Map of the Northern Region (pre-2020) in Ghana, highlighting the case study site Duko and the regional capital Tamale (black circles).

are described as cereal root crop mixed farming systems (Dixon et al., 2020). For Northern Ghana, Kuivanen et al. (2016a, 2016b) and Signorelli (2016) developed farm typologies for smallholders that grouped farms and farmers according to their resource endowment. Michalscheck et al. (2018) consolidated and combined their insights into a framework describing a vertical (within) and a horizontal (among households) dimension of diversity in local farm systems. In Duko, low resource endowed (LRE) farm households are characterized by small land holdings (0.8–2.0 ha), mostly growing maize, rearing no or only few livestock (poultry) and having no private means of motorized transport, at most a bicycle. Medium resource endowed (MRE) households typically cultivate about two hectares of land, rearing sheep or goats, and likely owning bicycles and/or a motorbike. The relatively high resource endowed (HRE) households in Duko may cultivate four hectares or more, likely owning cattle, small ruminants and poultry; their houses have zinc roofs instead of thatch and most likely they own one or more motorbikes or even a small lorry (*motor king*). Figure 3 illustrates three case study farms, which are selected actual farms each representing one farm type (Michalscheck et al., 2018). We applied the outlined farm typology to systematically describe differences among and within local farm households in terms of their resilience and the utility of the different technology packages.

3.4. Technology packages

This study was conducted in collaboration with the Research for Development (R4D) program Africa RISING (Research in Sustainable Intensification for the Next Generation) in Ghana. Since 2013, Africa RISING has been operating a so-called ‘technology park’ in Duko. The technology parks are community-based experimental stations, enabling the demonstration and evaluation of new agricultural technologies and facilitating a farmer-to-farmer knowledge exchange. In the technology parks, each trial includes a control field where farmers grow crops in the traditional manner and a treatment field, where a new technology is tested and compared to the control. Selected farmers also implement trials on their own fields, whether as baby trials (15×15 m^2) or upscaled trials (0.405 ha), for which they receive farming guidance and inputs (seeds, fertilizers, chemicals) from Africa RISING.

For the assessment of the farm’s adaptive capacities, we considered seven of Africa RISING’s technology packages (Table 1): one sole maize package (P1), three legume packages (P2, P3 and P6), two maize-legume intercrop packages (P4 and P5) and one livestock package (P7). The suitability and impact of P1-P5 have been described, modelled and discussed with farmers by Michalscheck et al. (2018). We complemented the existing assessment, by adding the farm-type specific suitability and adoption of P6 and P7 (cf. Section 3.4), capturing related data during field work in November 2019. Table 1 lists and describes each technology package with the assumed changes (inputs, yield, labour) per hectare as compared to the respective traditional practice. For P1-P3 the information about inputs and yields was obtained from project agronomic trial data (Kotu et al., 2016; Larbi et al., 2016a, 2016b). Assumptions on yield increases associated with the maize-legume intercrops (P4 and P5) were based on preliminary trial results (Kotu et al., 2017) and literature from West Africa (Dakora et al., 1987; Dakora & Keya, 1997; Horst & Hardter, 1994), assuming the

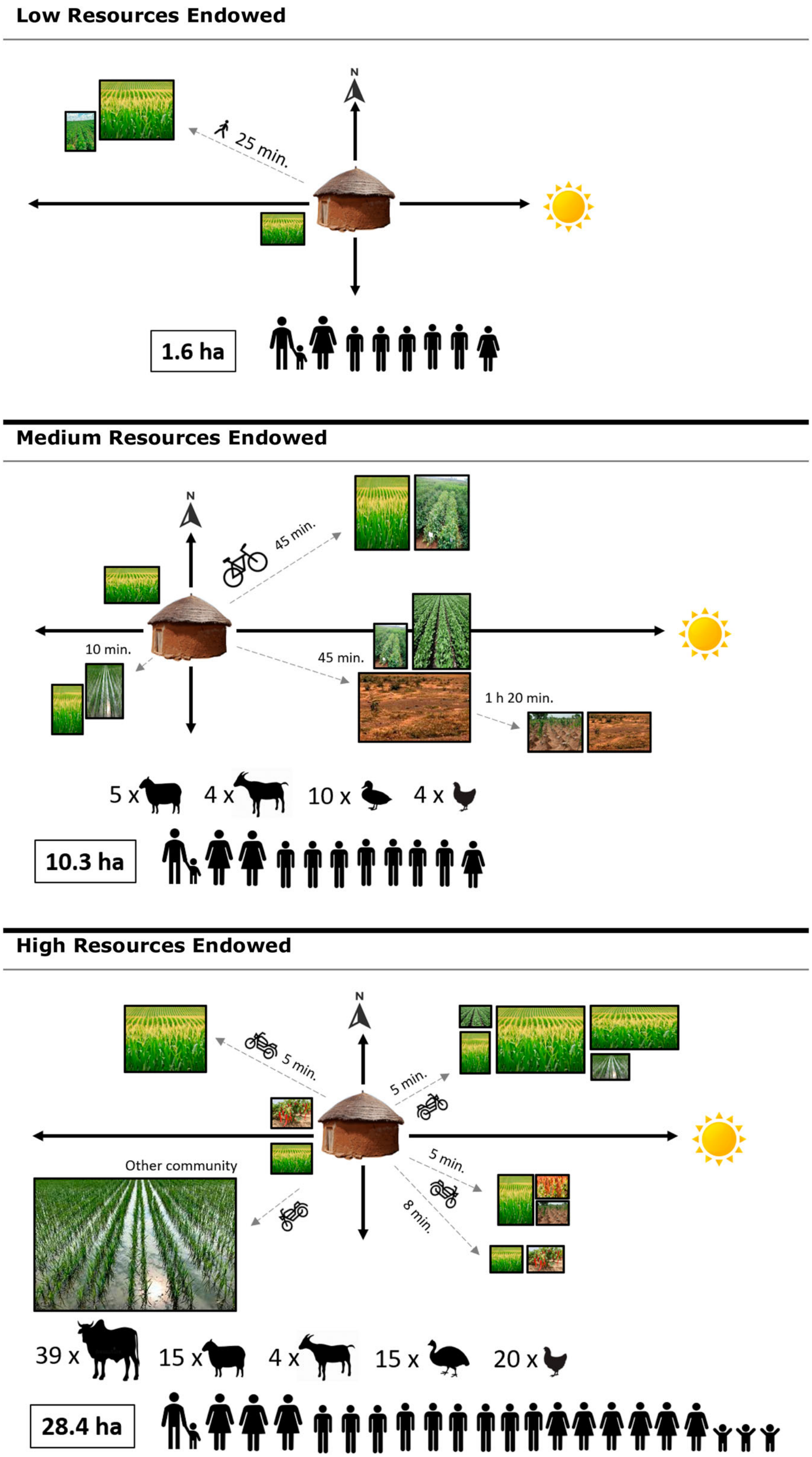
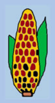
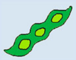


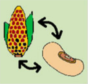
Figure 3. Graphical illustration of threecase study farm households in Duko (adapted after Michalscheck et al. (2018)).

Table 1. Description and assumptions of Africa RISING technology packages (P1–P7) as used in the FarmDESIGN model (adapted after Michalscheck et al. (2018)).

Package #	Description[a]	Assumptions	Traditional practice[b]
P1 **Sole maize** 	Fertilizer application on **maize**: Improved seeds, row planting and double the 'traditional' amount of sulphate of Ammonia (SA)	Fertilizer: 247 kg ha^{-1} NPK (15:15:15), 247 kg ha^{-1} SA (total: 90 kg of N ha^{-1}) Seeds: Improved seeds (cost: 3.3 GHS kg^{-1}), 21 kg ha^{-1}, row planting Average additional labour: 2.5 h ha^{-1}; Assumed yield increase: 25%	Fertilizer: 247 kg ha^{-1} NPK, 123 kg ha^{-1} SA (total: 60 kg of N ha^{-1}) Seeds: recycled seeds, 5 kg ha^{-1} Seeds planted haphazardly along ploughing lines
P2 **Sole legume** 	Improved **cowpea** variety (e.g. IT 99K 573-1-1), row planting and three sprays with Lambda cyhalothrin (2.5%)	Seeds: 20 kg ha^{-1} (cost: 6.7 GHS kg^{-1}), row planting sole cowpea Additional labour (harvesting): 2.5 h ha^{-1} Labour (per spray): 1.24 h ha^{-1} Assumed yield increase: 45%	Africa RISING uses 'one spray' as a control trial. Seeds: 10 kg ha^{-1}, improved variety
P3 **Sole legume** 	Integrated Soil Fertility Management (ISFM) on **soybean** including inoculum and Triple Super Phosphate (TSP)	TSP: 123 kg ha^{-1} (2.5 GHS kg^{-1}) Inoculum: 0.247 kg ha^{-1} (200 GHS kg^{-1}) Seeds: 37 kg ha^{-1} (cost: 4.6 GHS ha^{-1}), row planting; Total additional labour: 18 h ha^{-1}. Assumed yield increase: 50%.	No fertilizer Seeds: 37 kg ha^{-1}, broadcasted

(*Continued*)

Table 1. Continued.

Package #	Description[a]	Assumptions	Traditional practice[b]
P4 **Maize-legume** 	**Maize-legume rotation** with 2/3rd of the area grown with maize and 1/3rd with a legume (cowpea or soybean). If the farm area is large enough a 1:1 rotation was assumed.	Traditional fertilizer/spray on maize and legumes Additional labour: Maize (+2.5 h ha^{-1}) Cowpea (+5 h ha^{-1}), Soybean (+1.24 h ha^{-1}) Assumed yield increase for rotated maize: 50% compared to maize after maize Cowpea: 2 sprays, 20 kg ha^{-1} seeds. Soybean: no fertilizer	Continuous cultivation of maize
P5 **Maize-legume** 	**Maize-legume strip cropping**: 2 rows of maize, 2 rows of legume, with rotating strips from one year to another	Same as for the rotation, except labour: Maize (+3.7 h ha^{-1}) Cowpea (+7.4 h ha^{-1}), Soybean (+1.85 h ha^{-1} compared to the baseline).	Continuous cultivation of maize (possibly with intercropped legumes)
P6 **Sole legume** 	Improved **groundnut** variety (mani pinta), row planting, spacing (30 cm × 15 cm)	Seeds: 37 kg ha^{-1} (cost: 6 GHS kg^{-1}), row planting sole groundnuts; Additional labour (harvesting): + 10%; Assumed yield increase: 80%	Seed variety: 'Chinese', recycled; Spacing: 70 × 15

P7 **Livestock** 	Vaccination, deworming and concentrate feed for **small ruminants**	Annual PPR vaccination (2 GHS), bi-annual deworming treatment (each 3 GHS); 3 months of concentrate feed: 22 GHS	No vaccination, no deworming, residues and milling waste fed to the animals during the dry season whenever available, otherwise: free range.

[a] All packages furthermore promote the use of residues as green manure or livestock feed instead of burning.

[b] The traditional practices served as a reference to reset each case study farm to a baseline i.e. to a state without any of the described Africa RISING technology packages.

most conservative yield increase (50%). Data for P6 (groundnuts) was obtained from Rahman et al. (2020) while information on P7, the livestock package, was based on Konlan et al. (2014) and Avornyo et al. (2019, Personal Communication; 2015). The assumptions on labour increases and costs for the different package components of P1-P7 were based on consultations with farmers, Africa RISING staff and Ministry of Food and Agriculture local extension agents. Costs are indicated in GHS (1GHS = 0.13 USD, 18.05.2022).

The study took place when farmers had already partially adopted and adapted the technology packages. On the one hand, this provided us with valuable evidence on farmers' actual preferences and choices towards the proposed technologies. On the other hand, to determine the effect of the technologies, we needed to compare the farm with and without the technology packages, which is why we reset the three case study farms to a baseline, with only traditional and no project-proposed practices. We considered the exploration of the farm's adaptive capacities as *ex-ante* assessments, since we compared past states with possible future states of implementation that had not (yet) been reached (Michalscheck et al., 2018). The information on technology packages was complemented by farmer consultations on shocks.

3.5. Farmer consultations

In the process of defining the shock scenarios, we consulted 22 randomly selected farmers in Duko (20 men and two women, including the three case study farm household heads or representatives) as well as the Africa RISING lead farmer. The farmer feedback indicated the importance to include illness, death and out-migration as causes of labour shocks and determined the selection of the locally more important weather shock, namely drought rather than flood. The shock descriptions were as detailed and as precise as possible, ensuring consistence so that any difference in reported vulnerability or coping strategy would indeed be associated to differences in farm resources, capacities and strategies and not caused by a different interpretation of the shock scenarios. We revisited the same case study households described in Michalscheck et al. (2018). We recorded changes in household composition, land use and adoption of technology packages since 2015 to capture the development trajectories per farm.

Despite capturing the farm configurations of 2019, our resilience assessment refers to the year 2015, combining the more elaborate existing farm models from 2015 with the most recent knowledge about actual responses to shocks as well as the resulting farm trajectories. We furthermore systematically (cf. household survey in S. Annex 1) collected data on farmers' estimations of the impacts per shock scenario in order to obtain accurate input data for the model-based whole-farm vulnerability assessment. We also interviewed various household members of our case study farms about the estimated speed of recovery after each shock type and about their strategies for overcoming each shock in order to assess how the model-proposed recovery options fit with their existing coping strategies. Due to time constraints, we interviewed the male household head or their representative (a son of the HRE household) of the case study farms.

To contextualize our findings, we furthermore conducted a short resilience-assessment survey (see S. Annex 1 involving 20 men and 2 women). Respondents were asked to evaluate their resilience, at household- and at individual level, on a scale from 0 to 10, with 0 expressing no robustness or resilience (high vulnerability with no means of recovery) and 10 being fully robust or resilient (shocks do not affect the household or they can fully recover immediately). Participants were also asked to evaluate their willingness to change farm practices in response to the shocks they face, with a score of 0 indicating no changes and 10 expressing radical changes. We furthermore asked for an evaluation of the respondent's satisfaction with their current resilience, with 0 indicating 'no satisfaction' and 10 'full satisfaction'. For all above-mentioned evaluations (0–10) we used the so-called stick-score method developed by Michalscheck et al. (2019) for measuring abstract concepts like levels of satisfaction and power shares among smallholders. To explore the transferability of our findings from Duko (Northern Region), we held Focus Groups Discussions (FGDs) in each of two other project intervention sites, Nyangua (Upper East Region) and Zanko (Upper West Region), collecting famers' perspectives on the relevance of the four shocks as well as their coping strategies. The FGD findings are presented briefly in the discussion section, when reflecting on the transferability of our insights from Duko. All consultations with local project staff and farmers took place in November 2019. The survey data is provided in S. Annex 3. The farmer consultations constituted a core input for the definition of the four relevant shock scenarios.

3.6. Shock scenarios

Besides the farmer consultation, we interviewed academic experts and project staff (F. K. Avornyo, personal communication, 2019; F. Kizito, personal communication, 2019; B. Kotu, personal communication, 2019; S. B. Mellon, personal communication, 2019; I. B. Mohammed, personal communication, 2019), reviewed literature (Bariw et al., 2020; Friesen, 2002; Jarawura, 2014; Mewes, 2018; Olugbenga, 2017; Tambo, 2016; Tambo & Wünscher, 2017) and available data sets (2019) for the case study location. We identified and defined four severe shock scenarios that farmers in Duko may be exposed to:

- *A severe drought:* four weeks of no rainfall in June or July. A time that marks the start of the growing season where crops are tender and in critical growth stages like germination and dry matter accumulation.
- *A severe Fall Army Worm (FAW) infestation:* if no preventive action was taken, 50% of the total plant population would be heavily infested, resulting into maize yield losses of about 60%.
- *A severe reduction in crop product prices (a price shock):* assuming that market prices for maize drop by 50% and by 20% for rice, millet, yam and cassava due to bumper crop and high market supply.
- *A severe reduction in household labour availability (a labour shock):* 50% of total household labour is unavailable during the peak season (e.g. harvesting) due to illness, death or sudden outmigration.

Concerning the probability of each of the severe shocks, households were asked about the frequency at which these would occur respectively (S. Annex 3). Their indications on shock frequencies differed, since the same event would affect households differently, ranging from 5–10 years for a severe drought shock, 4–6 years for a severe price shock, 3–20 years for a severe FAW infestation and 2–10 years for a severe labour shock. Regarding the interdependence of the selected shock events: price and yield shocks may reinforce trends of temporal or permanent outmigration, possibly leading to a labour shock. Various additive shock scenarios could be considered and run through the same farm models that we built for the individual shock scenarios. This paper focuses on individual shock scenarios, serving to unpack differences in resilience among farms and farmers. S. Annex 2 provides an overview of the four shock scenarios including their general as well as farm-type specific impacts on individual farm components such as crop yields and labour availability, serving as input-data for the FarmDESIGN model.

3.7. The FarmDESIGN model

We employed the whole-farm model FarmDESIGN to assess the resilience i.e. the vulnerability, the buffer and adaptive-capacity of a representative LRE, MRE and HRE farm household in Duko. FarmDESIGN is a bio-economic, static model with a multi-objective optimization algorithm (Groot et al., 2012). FarmDESIGN may hence be used for a detailed analysis of the farm performance and resource flows, describing a farm's physical components (field, buildings, animals, crops, organic matter imports), inputs (capital expenditure, labour, fertilizers, pesticides, seeds) and outputs (income, grain yields, animal products). FarmDESIGN also captures information on household composition, labour contributions, off-farm income and expenses (Ditzler et al., 2019) as well as environmental data such as information on the local climate, soils and economic parameters like the national interest rate as well as costs for labour and land. Crop and livestock components are integrated. Due to the built-in multi-objective optimization tool, FarmDESIGN may be used to generate many Pareto-optimal, alternative farm configurations (solution cloud). For the optimization (exploration), we chose three objectives, representing the economic and environmental sustainability, namely to maximize the annual farm operating profit (GHS yr^{-1}), labour savings (hours yr^{-1}) and the soil organic matter (SOM) balance (kg ha^{-1} yr^{-1}). The farm profitability indicates the contribution of the farm enterprise to household income. The labour savings are important to allow the household members to engage in other activities on- or off-farm. The SOM balance indicates whether there is net build-up (positive values) or degradation (negative values) expected given the balance between inputs (e.g. crop roots and stubble, manure) and decomposition (e.g. soil organic matter pool). The SOM balance is important for soil health and water holding capacity. Decision variables (i.e. variables the model could alter in the optimization process) included the crop-specific size of individual and household fields, quantities of feed imported and crop residue allocation. Each generated farm configuration thus constituted a possible farm future, with defined crop and livestock types, respective field or herd sizes as well as management practices towards the set farm objectives. Being a static model, FarmDESIGN models are 'snapshots' in time, representing a one year-period, requiring cumulative annual figures such as crop yields or labour inputs. We worked with version 5.1.0 of FarmDESIGN (https://fse.models.gitlab.io/COMPASS/FarmDESIGN/), using the farm models described in Michalscheck et al. (2018).

To model the four shock scenarios, we consulted members of the three case study households on the impact of the shocks on their crop yields, livestock productivity, livestock mortality, labour requirements and sales (Section 3.4). We also consulted agricultural experts ($n = 5$) including an extension officer, local project and university staff, about the impacts of the shock scenarios on local markets as well as on crop and livestock productivity. We used the insights to manually implement the shocks on each of the baseline farm models, subsequently using the shocked farms for computing the resulting solution spaces (room to manoeuvre) without (buffer capacity) and with (adaptive capacity) the SI technology packages (cf. Section 3.3).

S. Annex 2 provides details on the model assumptions and decision variable ranges per scenario. To explore the adaptive capacity, the model was able to adopt the project proposed technology packages or to maintain the current practices, aiming to improve farm performance within the given constraints such as livestock feed requirements and spatial limitations. After setting the decision variables, constraints and objectives, we ran the exploration in FarmDESIGN for 1000 iterations, generating solution clouds of alternative farm configurations. The solution clouds served for a visual comparison of buffer and adaptive capacities as well as to determine the respective attainable maximum values per optimization objective. We modelled 39 farm configurations: per farm type one baseline, four shocks and per shock a model respectively to explore the buffer capacity and the adaptive capacity. All modelled farm configurations may be downloaded as part of the supplementary materials (S. Annex 4). The assumptions and changes underlying individual models are also explained in the respective FarmDESIGN notes, accessible via the model user interface.

4. Results

4.1. Farm trajectories (2015–2019)

Preparing for, coping with and recovering from shocks takes place in a complex and highly dynamic environment, shaping and being shaped by the overall development trajectory of a given farm household. We hereby outline the farmer-reported farm-specific development trajectories, the adoption status of the different technology packages and the main changes in their on- and off-farm activities between 2015 and 2019.

The LRE farm household increased its farm area (+88%, from 1.6 ha to 3 ha, albeit of low soil quality) and grew a larger variety of crops including rice, yam, okra, tomato and pepper. The LRE household also started rearing poultry, keeping about 20 fowls, and the oldest son left the community for off-farm labour without sending remittances, corresponding to a labour shock. The household head reported to have worked hard, preparing most of the household farmland by hoe, in order to gradually increase the households' income. His wife increased her trading activity and was reported to have been successful in generating an extra income, too. The LRE household seemed to have improved its situation but could still be considered of low resource endowment. Among the technology packages, only P1 (maize) seemed to be relevant to the LRE farm household, since even in 2019 the household did not grow any legumes and had no small ruminants.

The MRE household was strongly affected by a conversion of community farmland into building plots, losing about 2 hectares (20%) of their available farm land. 84% of the household's income was derived from on-farm activities and sales. The MRE household started growing teak trees, possibly to assert its long-term claim on its remaining parcels to avoid the further loss of farmland. The household head indicated to plan a stronger focus on livestock rearing to reduce his dependency on the shrinking farmlands for crop cultivation. In 2019, the MRE household grew P2 (cowpea) and implemented P4 (a rotation of maize with soybean and groundnuts) but was not aware of P7 (the feed and health package for small ruminants). We hypothesize that adopting P7 could, nevertheless, be interesting for the MRE household, since sheep and goats were indicated to be the main livestock assets and source of resilience for the household.

Similar to the situation in 2015, the HRE household in 2019 was still heavily involved in both crop and livestock farming, by rearing cattle, and growing cash crops like groundnuts, rice and vegetables. The household started rearing guinea fowl and typically sold livestock in times of crop failure. The household also owned a tractor, a bore hole, a mill, a small supermarket in the community and other assets that they rented out or used to provide services. We estimate that in 2019 only about 30–40% of the HRE household's income was derived from farming. Concerning the technology packages, the eldest son of the HRE household indicated that they did not use the recommended fertilizer rate on maize (P1), since yields were sufficiently high at lower rates. The son further indicated not to be interested in P3 (soybean) since soybean, compared to other crops, was too labour intensive and the fields, where the household would need to plant it, were relatively far away. The strip crop (P5) was considered as too labour intensive, too. Only few farmers in Duko were reported to practice it.

4.2. Vulnerability to shocks

In 2015, the three case study farms had different starting positions in terms of their farm operating profit, labour and soil organic matter balances (Figure 4): per unit of area, according to FarmDESIGN, the MRE household had the lowest profit (229 GHS ha^{-1} yr^{-1}), labour input (228 h ha^{-1} yr^{-1}) and SOM balance (−802 kg ha^{-1} yr^{-1}). The LRE household showed a greater profitability (318 GHS ha^{-1} yr^{-1}) and labour input (335 h ha^{-1} yr^{-1}) than the MRE farm and the least negative SOM balance (−372 kg ha^{-1} yr^{-1}) among all three farms.

When comparing the farm performances at shocked state relative to the baselines (Figure 5), the FarmDESIGN results suggested that the severe drought would have the most drastic impact for all three farms, causing the greatest reduction in SOM, but also the highest labour savings among the shocks. For all three farm types, the severe drought shock would, according to the model, lead to a negative operating profit (a negative profitability), so that all three farm households would have to use their savings or run side-businesses in a severe drought year. Modelled profits of the MRE (−166%) and HRE (−153%) farm were most impacted by drought, while the modelled profit of the LRE farm was most affected by the price shock (−126%), closely followed

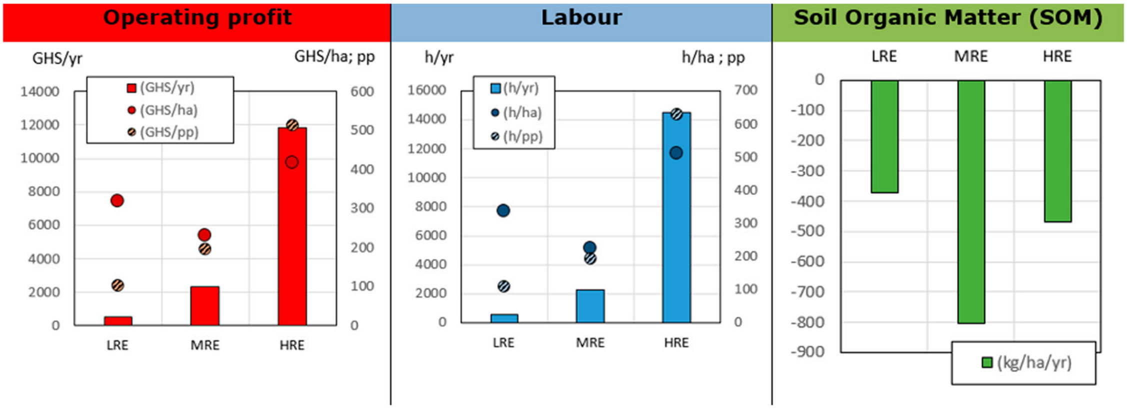


Figure 4. Overview of modelled farm performances at baseline (pre-shock, 2015) in terms of the operating profit (GHS per year (yr^{-1}), per hectare (ha) or per person (pp)), the labour input in hours (h) and the soil organic matter (SOM) balance (kg ha^{-1} yr^{-1}). For reference, 500 GHS correspond to 65 USD, 10.000 GHS to 1300 USD (1GHS = 0.13 USD, 18.05.2022).

by the drought (−111%). According to FarmDESIGN, the labour shock severely impacted the MRE farm household, too, reducing its profits by 90%.

Concerning the case study farmers' self-reported vulnerability in terms of profit cutbacks and resulting food insecurity, the respondents of all three case study farms evaluated the drought shock as the most severe. In line with the model results, the MRE household evaluated the labour shock as severe, too. In fact, according to the respondents of the LRE and MRE household, if labour falls short, due to illness, death or out-migration, farmers who do not manage to immediately mobilize compensatory labour, struggle to maintain their farm activities, leading to yield losses due to untimely weeding or harvesting. In case of illness, the burden was highest, since ill household members require the care, feeding and financial support of the remaining healthy household members. When asked which shock the respondents would address first if they were able to remove one of the four, both the LRE and MRE respondents pointed towards the labour (health) shock rather than the drought shock, possibly indicating a high importance of socio-emotional stability, too. Out-migration was reported to have the advantage that fewer people in the household need to be fed and that, at times, those who return from or remain in off-farm jobs, provide remittances that support the

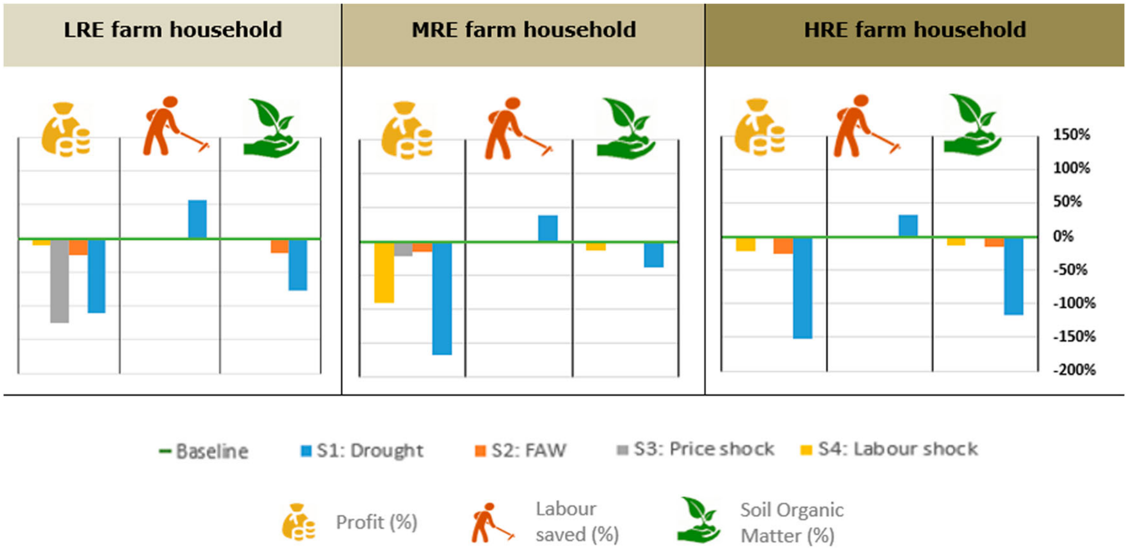


Figure 5. Percentage change in modelled farm performance (profit, labour, soil organic matter) of the LRE, MRE and HRE farm households due to the drought, pest, price and labour shock respectively.

household. Concerning the changes in labour needs, all respondents indicated that yield reducing shocks would reduce labour demand, since they would weed less and harvest less. While the MRE and HRE respondents seemed unable to estimate overall labour savings, the LRE household head reported 30% lower labour needs in times of drought. However, the labour savings were overshadowed by the foregone food and profit, particularly since the redundant labour could not easily be turned towards a similarly productive alternative activity.

Both model results (Figure 5) and farmers self-reports (Figure 6) indicated that the price shock would strongly decrease farm profits of the LRE and MRE households, while it would have no effect on the HRE farm. The different impacts of the price shock seemed to depend on whether a household was a net buyer or net seller of cheap maize: the HRE household reported having the capacity to buy cheap maize and later re-sell it for a higher price, making profit in times of the price shock. Farmers of all household types stated that the price shock would not have an impact on their food security. Both the whole-farm model results and the farmer self-reports indicate that the MRE farm household seemed to be the most vulnerable among the three farm types in terms of its operating profits, particularly in times of a severe drought, price or labour shock.

Concerning the vulnerability of individual household members, a local extension officer hypothesized that the FAW infestation and consequent maize yield reductions would affect the male household heads most, since they were responsible for their household's food security, while women rather grew vegetables and groundnuts and young men typically farmed rice. The drought could particularly affect women too, since they were responsible for fetching water and water levels would temporarily be lower or nearby wells would be dry. This did not seem to be an issue for women in Duko, since there was a public water pump in the village centre resulting in good reach of water for all homesteads of the community.

4.3. Recovery

This section presents model-based results on the farms' room to manoeuvre after each shock as well as narratives on shock-specific coping strategies at individual and household-level, jointly reflecting potential recovery strategies per farm and farmer type.

4.3.1. Model-based explorations: adaptive and buffer capacity

Comparing the rooms to manoeuvre after shock (Figures 7 and 8), we found that for all farms, the addition of project proposed technology packages (Table 1) would increase their capacity to recover or to improve their performance as compared to the respective baselines.

The LRE farm household would only have a few options to change its farm configuration, but these few changes would make a big difference in the recovery from most shocks. The ability to recover from the drought and the price shock was high, even without the inclusion of the new technology packages, indicating a considerable buffer capacity (Figure 7). Adding P1 (maize, including green manure application) would significantly improve the soil organic matter balance, while labour savings and operating profits would only marginally increase as compared to the buffer capacity. Generally, the LRE farm's ability to recover its profitability would be limited, barely reaching or surpassing the original profitability at the baselines even when including P1. Only after the labour shock scenario, FarmDESIGN identified configurations that allowed a notable profit increase (+21%). There seemed to be no (immediate) financial recovery for the LRE farm household after the FAW infestation, due to the high infestation level for both, the traditional and the P1 maize, which strongly determined the farm's income.

The MRE farm household would have a larger room to manoeuvre for its recovery than the LRE farm household. While the technology packages would add little to the MRE household's performance in terms of labour savings or the soil organic matter balance, they would substantially increase the farms' operating profit, especially after the FAW infestation (+122% compared to baseline) and after the price shock (+106%) (Figure 7). Concerning alterations in farm configurations after drought (Figure 8b), the main change when compared to the baseline was the reduction of total farmland, mainly by reducing fallow land as part of farmland from 5.6 ha to 0.89 ha on average. The number of local sheep and goats was also reduced from five sheep and four goats at baseline to an average of three each for the buffer and the adaptive capacity. Furthermore, we observed a decrease in maize area: on average −16% for the buffer and −10% for the adaptive capacity as compared to the baseline area of 1.9 ha. We also noticed

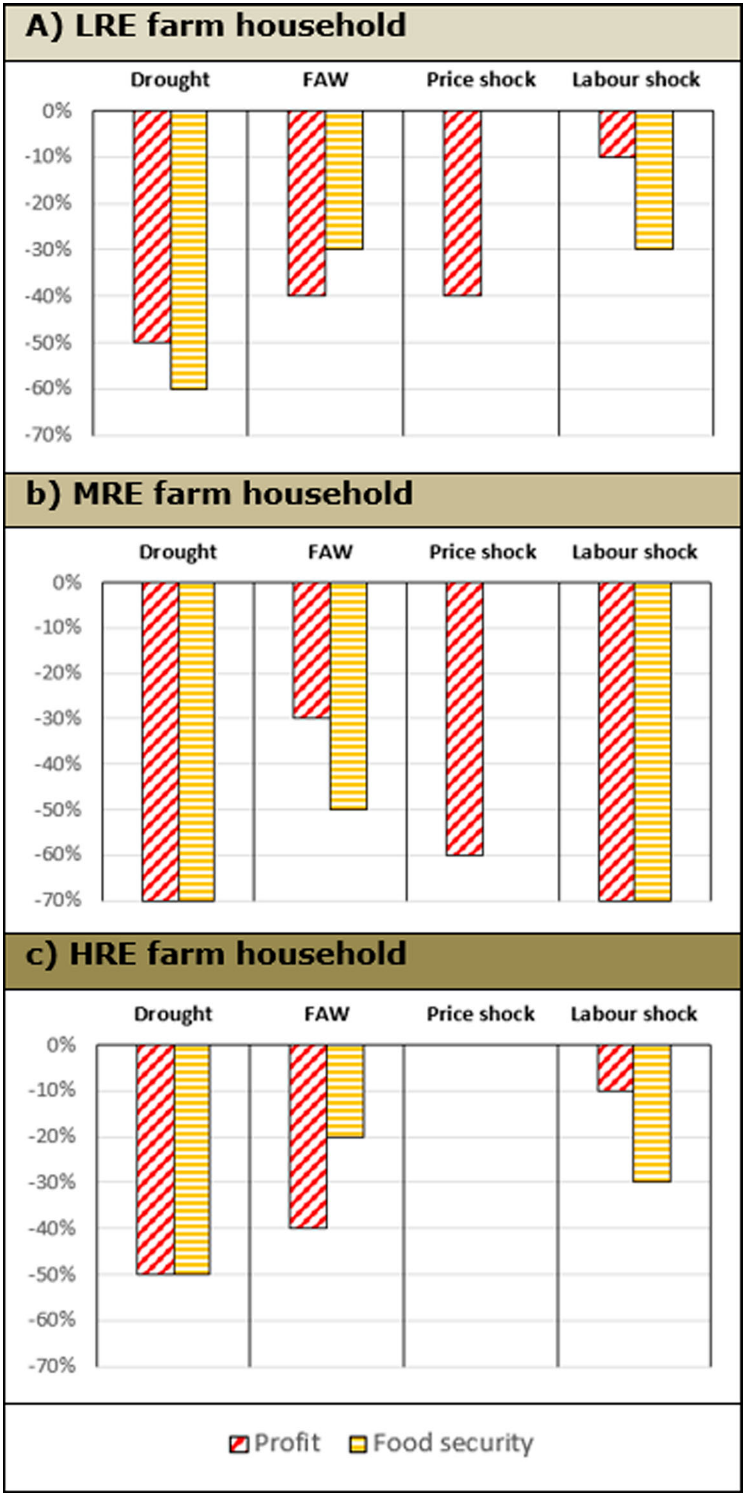


Figure 6. Expected change in farm profit and household nutrition as stated by farmers from low (LRE; a), medium (MRE; b) and high (HRE; c) resource endowed farms in response to drought, fall army worm (FAW) infestation, a reduction in product price or and a reduction in available labour.

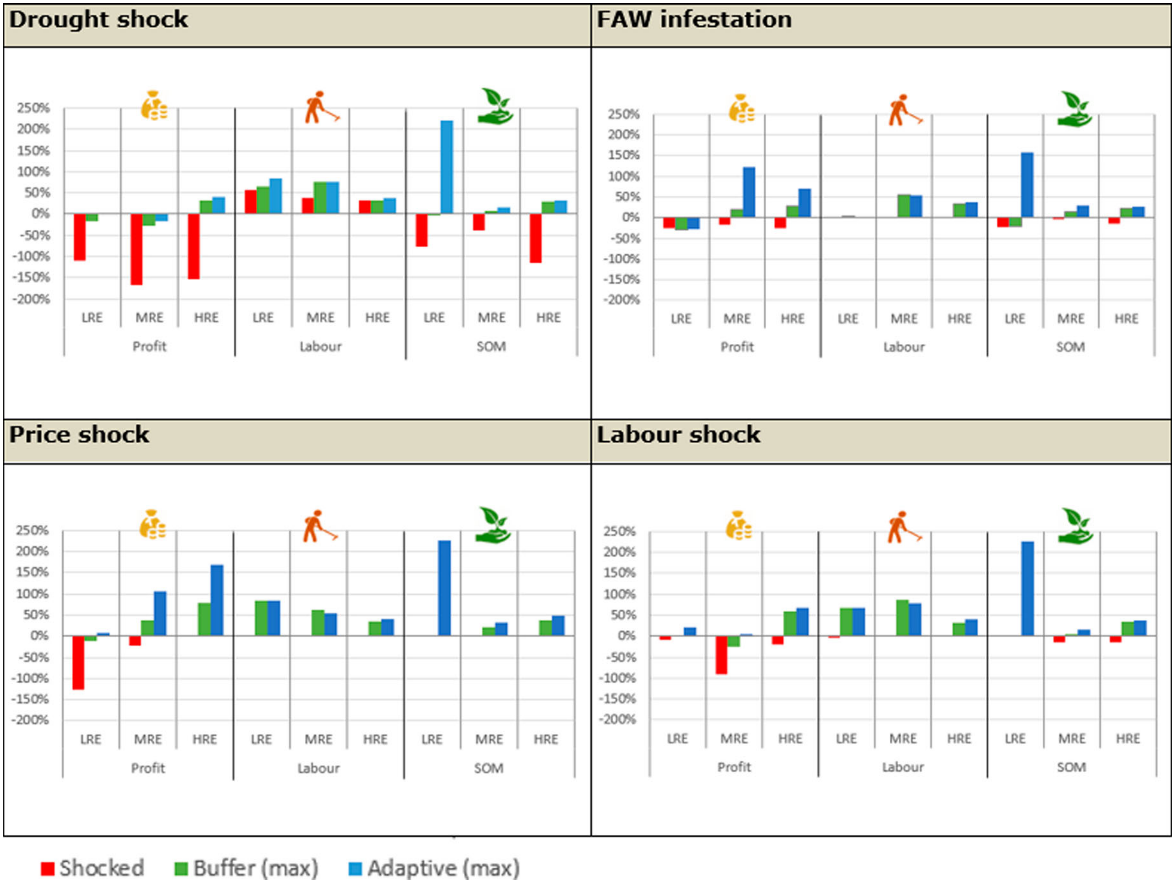


Figure 7. Impact and recovery from shocks as compared to the baseline for the LRE, MRE and HRE farms (FarmDESIGN results). The red bars indicate the shock-specific percentage change in farm profit (GHS/yr), labour savings (h/yr) and SOM (kg/ha/yr). The green and blue bars indicate the maximum percentage improvement as compared to the baseline for the buffer and adaptive capacities respectively.

an initial cut-back and then gradual increase in soybean (max: 19%, P3 max: 14% of total farm area) and cowpea areas (max: 8%, P2 max: 2% of total farm area) with increasing profits. After the drought shock the MRE farm household was not able to fully recover in terms of its operating profit: the best performing configuration in both, the buffer and the adaptive capacity, remained 17% under the profitability at the baseline. After the labour shock, the maximum profit attainable as part of the buffer capacity remained 25% below the baseline. However, including the technology packages (optionally P1, P2, P3, P4, P6 and/or P7) could lead to an increase in the attainable profit to 6% above the baseline.

For the HRE farm household, all model-generated maximum values for all objectives and after all shock scenarios, for both the buffer and the adaptive capacity, would constitute an improvement in comparison to the pre-shock performance at baseline. Even for the worst shock, the severe drought, in which the HRE farm household would experience a strong drop in operating profits and its soil organic matter balance, the farm household would be able to recover and supersede the baseline performance in all objectives by about 30–40%, even without adding new technologies. For both MRE and HRE households, operating profit was the indicator with the greatest possible improvements when including the project proposed technology packages. The improvements in labour savings or soil organic matter were minimal when allowing the model to add the new technology packages (optionally P1, P2, P3, P4, P6 and/or P7). FarmDESIGN exploration results indicated that more area should be allocated to the traditional crops rather than the project

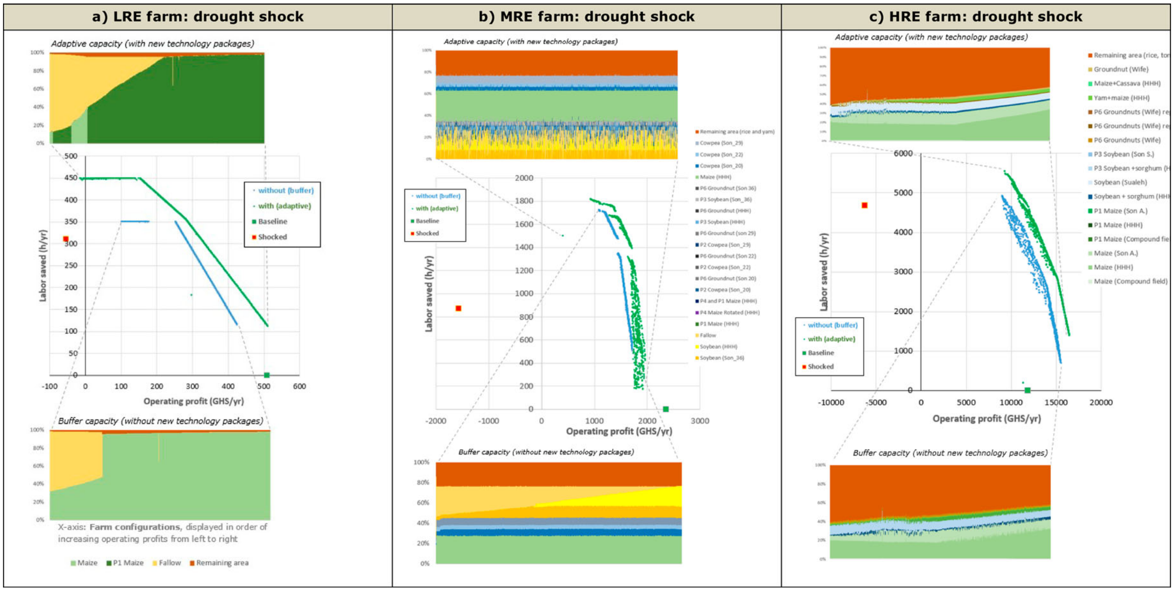


Figure 8. Solution clouds for (a) the LRE, (b) the MRE and (c) the HRE farm household, depicting the buffer and the adaptive capacity per household after (one of) the most severe of all shocks, the drought shock. For each solution cloud, a stacked bar-chart is provided, illustrating changes in allocations of area to the different crops, sorted in order of increasing operating profits.

proposed technology packages (Figure 8c). The only packages that were chosen for the HRE farm were P6 (groundnuts) and P7 livestock (particularly sheep). However, the maximum area that the model allocated to P6 was only 0.2 hectares (0.7% of the farm area). Furthermore, P7 sheep were only added after the defined maxima for traditional sheep and goats were reached, again indicating a greater preference for the traditional farm elements.

4.3.2. Farmer-reported coping strategies

In addition to modelling the buffer and adaptive capacities of the three case study households, we asked 22 farmers in Duko to describe their risk mitigation and coping strategies as part of their transformative capacity, illustrating a variety of preparatory measures and recovery trajectories for different local farms and farmers. Respondents reported that mainly the male household members relied heavily on livestock sales ($n = 19/22$) in years with low crop yields due to a drought or a crop pest. Depending on their resource endowment and financial need, farmers sold poultry, small ruminants or cattle. However, livestock mortality rates were high and animals often fell ill and died. Increasingly frequent, animals suffer from ingested plastic waste (Figure 9). Furthermore, livestock theft has become very common. Mostly at night, fowl, small ruminants or even cattle have been stolen, with all farm types being affected. The high mortality rates and theft make livestock rearing unprofitable. Nevertheless, farmers continue to buy, rear and sell animals, since livestock is also used for cultural purposes, religious ceremonies, gifts, as a savings account and in fact, as an insurance in times of shock. Survey respondents who thought that livestock were important for resilience (76%), estimated, on average, that improvements in animal feed, health, breed or a lower mortality rate could increase household-level resilience by +35% ($s = 0.153$). It was livestock sales, the ownership of assets and lands that made most men ($n = 11/19$, 58%) feel more resilient than other members of their household, indicating gendered resilience capacities and attributes.

While livestock in Duko mostly belonged to the men, women reported to have other coping strategies to support their households in times of shock: they collected and processed shea nuts into shea butter, which they sold on local markets (Figure 10). They also collected the edible pods of the carob tree and processed it into a local specialty called *dawadawa* (Figure 11), that their household ate and sold. Women in Duko also bought, processed and re-sold rice (Figure 12). Since women in Duko are successful traders, they were able to lend money to their husbands for hiring labour, for agricultural (e.g. ploughing) services or for purchasing inputs. Women reported to insist on the repayments by their husbands, so they were not held back in their own business and duties. Of the male respondents 32% ($n = 6/19$) indicated to feel less resilient than their wives, due to their wife's strength and more stable income through trading. Both men and women reported to be members of money saving groups, so called susu-groups (from *akan* '*susu*' = 'plan'): all members made weekly contributions of a few Ghana Cedis, subsequently entitling them to take out small loans. Particularly during and after shocks, susu-loans provided direly needed capital to maintain or re-start income-generating activities. Members of Susu-groups reported high repayment rates, but also that they feel constrained by the low total capital that they were able to raise. They indicated to feel that their farm and off-farm businesses could go much further if they had a link and access to larger and formal micro-finance institutions.

In addition to the above-mentioned general diversification and coping strategies, farmers reported that the technology packages from development projects also helped them to be more resilient: the provided inputs as a result of Africa RISING project interventions (seeds, fertilizer) for one acre of maize (mentioned by 90% of responding project beneficiaries), and agronomic practices like row planting, the use of improved seeds, the choice of the right planting time, the use of compost and micro-dosing of fertilizer, were reported to increase yields, enabling farmers to build up a greater food and economic buffer, decreasing their vulnerability and allowing them to recover better and faster. On average, farmers reported an increase of +22% ($s = 0.08$) in their resilience due to the implementation of project proposed technology packages.

Concerning shock-specific coping strategies, in times of drought, the chosen planting time (early or late) and soil properties (dry or wet) were indicated to co-determine the severity of the yield losses. The LRE case study household planted at multiple moments to ensure that at least one share of the crops would yield well regardless of the weather conditions. Planting different crop varieties, some more and some less drought tolerant, was a coping strategy by the MRE case study household, but in times of a severe drought, as we defined it, none of the crop varieties was indicated to perform well anymore. Relatively drought tolerant quality protein maize (QPM) varieties such as *Omankwa* (early duration with 90 maturity days) and *Abontem* (extra early duration with 75–80 maturity days) were reported to only

Figure 9. Poultry in the midst of plastic waste in Duko, Northern Region, Ghana.

Figure 10. Shea butter, made from processed shea nuts, covered with fabric for better storage. Each bowl can be sold for 200 GHS (USD 26).

perform better in times of moderate drought i.e. one week of no rainfall during the most vulnerable crop growth stages. For the drought shock, farmers thus mentioned preparatory measures rather than a particular strategy to cope with or to recovery from it.

In times of a severe price shock, in general, the ability to store the grain and to sell it later, when prices would go up again, was identified as the main coping strategy, decreasing vulnerability.

Concerning the FAW infestation, farmers reported that applying a chemical spray commonly known as Ema Star 112EC (active ingredient: *Emamectin Benzoate* + *Acetamiprid,* 1.3%) was their main coping strategy, making them less vulnerable: a development

Figure 11. Dawadawa (carob mixed with soybean flour), to be eaten or sold in the market, Duko, Northern Region, Ghana.

Figure 12. Woman processing (soaking and parboiling) rice in Duko, Northern Region, Ghana.

project had taught farmers in Duko about the spray and how to apply it, significantly reducing FAW-related maize yield losses (20–40% instead of 50–70%). The MRE household head reported to produce and apply a self-made neem-spray instead. When comparing the reported effectiveness of the chemical spray (20%–40% maize yield losses for the LRE and the HRE household) and the neem spray (60% maize yield losses for the MRE household), the chemical spray seemed to perform better. Weather conditions also played a role in determining the infestation levels (Du Plessis et al., 2020): in 2019, the FAW infestation was reported to be less severe with farmers hypothesizing that the lower infestation was associated to the strong rainfalls washing FAW-caterpillars off their host plants.

In times of a labour shock, farmers reported that their social network was particularly important in order to mobilize communal labour i.e. people get together in groups and take turns working on each other's fields. Due to their small field sizes and their relatively greater subsistence orientation, the LRE farm household seemed to face the least problems in mobilizing communal labour, while the MRE and HRE farmers had to resort to hired labour, constituting a financial challenge for the MRE but not for the HRE farm household.

Putting the coping strategies into a medium to long-term perspective, we asked farmers how willing they actually were to make changes to their farm systems in order to decrease their vulnerability or to increase their ability to recover. On average, farmers reported a low willingness to change: a mean value of 1.6 out of 10 (0 = nothing at all, 10 = radical changes). About half (48%) of the respondents indicated to not change anything, even in times of or after a major shock. Among those respondents who would make changes, most (55%) indicated to change the crop varieties to short-duration ones, to increase the crop diversity (45%) and/or to change the planting time (45%) or location (36%). To increase their resilience, farmers envisioned an increase rather than a change in their existing activities, e.g. to increase their herd size ($n = 14/21$) and to expand their agricultural area ($n = 11/21$). While an increase in farm area has indeed been reported by the LRE household (+80% between 2015 and 2019), the trajectory of the MRE case study household demonstrates the increasingly limited possibilities for an expansion of good quality agricultural land in the community. The eldest son of the HRE household mentioned a different strategy: his household could be more resilient if (more) of their members had stable off-farm incomes through jobs in the nearby cities of Tamale or Savelugu.

Finally, we also inquired about the speed of recovery: the LRE household (head) indicated that it would take the household two years to recover from a severe drought, a severe price shock or a FAW infestation and one year to recover from the severe labour shock. The MRE household (head) estimated their recovery to take longer: four years to recover from the severe drought and two years from the severe price shock, the FAW infestation or the labour shock. The HRE household (eldest son) indicated that the household would already have recovered the year after any of the four shocks.

5. Discussion

The model results and farmer consultations jointly confirmed that all three farm types could become more resilient through the adoption of technology packages for sustainable intensification: by using good agronomic practices, farmers would be able to increase productivity which would allow them to build up a financial buffer, making them less vulnerable to shocks and empowering them to recover better and faster. While the LRE household's performance mainly improved in terms of its SOM balance, the MRE and HRE farms significantly improved their operating profits. The larger improvement in SOM for the LRE household through adoption of P1 maize, using crop residues as green manure, is ascribable to the high importance of crop-related soil fertility measures due to the absence of livestock (animal manure) (Michalscheck et al., 2018). The large potential profit gains for the MRE and HRE households were related to their larger range of choices among traditional and SI technology packages, implying a greater adaptability and transformability. A complementary study by Jansen (2020) showed that, for the same case study households, incorporating the technology packages was an attractive strategy to improve the households' nutritional resilience, too. Beyond farm activities within the project-proposed intervention focus (small ruminants, maize, legumes), farmers reported a broad range of additional coping strategies: men also reared poultry and cattle, depending on their resource endowment, while women collected and sold wild nuts and fruits and processed rice to generate an additional income. The same gendered economic activities have been reported in previous studies (Aniah et al., 2019; Apusigah, 2009; Assan et al., 2018; Kuivanen et al., 2016b; Mewes, 2018; Nyantakyi-Frimpong & Bezner Kerr, 2017). Particularly the collection of wild nuts and fruits has a positive side effect: it adds value to the renewable, non-wood products of local tree species, protecting e.g. shea trees (*Vitellaria paradoxa*, syn. *Butyrospermum parkii, Butyrospermum paradoxum*) from logging (Masters et al., 2004), despite a high local demand for firewood. Shea nut collection and processing does not only strengthen the resilience of women and their households, but also tests and revives the community cohesion, since the protection and the use of these trees requires a communal effort (Chen, 2017; Elias, 2015; Elias & Carney, 2007). Another coping strategy used by both men and women was the participation in money saving groups to steadily build up a small capital and to take out loans. According to Batung et al. (2022) access to credit services is indeed a decisive factor for smallholder farmers in Norther Ghana to build perceived (climate change) resilience. Furthermore, we found that good post-harvest storage was particularly important in times of a crop price shock, allowing farmers to postpone sales in order to eventually achieve better market prices. A strong social network was considered important in times of a labour shock, allowing farmers to effectively mobilize compensatory labour from the community.

Despite the positive outlook, all four shocks and in particular the drought were expected to severely impair the three case study farms. The severe drought would lead to negative operating profits, implying that farmers would have to live off their savings or side-businesses in a severe drought year. Studies by Tambo and Wünscher (2017) as well as Jarawura (2014) confirm that farmers in Northern Ghana are weakly resilient to climate shocks. Similar to our findings, Tambo and Wünscher (2017) further report that, beyond adopting externally driven technologies, farmers had developed their very own innovations and coping strategies, making innovators about 6% more resilient than non-innovators. Birthal and Hazrana (2019) refer to evidence from Nigeria and India, where many smallholders, particularly asset-poor farmers, despite various risk-coping mechanisms, were unable to recover after severe drought. Also in Duko, LRE and MRE households would be more affected than HRE farmers, struggling to recover after shocks. The LRE household would only have a very small room to manoeuvre and little options for change, barely able to re-attain its pre-shock profitability, particularly after the severe drought or the severe price shock. The MRE household would be vulnerable to the labour shock and the drought, anticipating to require the longest recovery time (of two to four years) among the three case study households. The high vulnerability and low capacity to recover might be a consequence of the MRE household trying to grow, to be more commercial, taking more risks than the LRE farm, without having the same fallback options as the HRE farm household with its off-farm side-businesses. At baseline, the MRE household had the lowest labour input and profit per hectare, possibly revealing a persistent labour constraint, which in turn might explain the severity of the labour shock to the MRE household.

Despite the strong general alignment of our model results with farmer realities, we observed a disparity for the exploration of recovery options after drought for the MRE household: while the model recommended a strong reduction in fallow land area, the MRE household in 2019 was worried about exactly this reduction, since it was limiting the household's ability to rotate crops, constraining their possibilities and profitability of arable farming. So why did the model suggest this change? Firstly, the reduction of the unproductive fallow land saved an assumed general land costs of about 145 GHS ha^{-1} yr^{-1} (GARBES, 2014). Secondly, fallow land has a relatively low value for effective organic matter (500 kg ha^{-1} yr^{-1} as e.g. compared to 1025 kg ha^{-1} yr^{-1} for cowpea or 1285 kg ha^{-1} yr^{-1} for soybean) so that reducing its area would automatically increase the farm average SOM per hectare, which FarmDESIGN was to maximize. The settings of decision variables and constraints could be further tuned to reflect that the fallow lands were an important part of the crop rotations, solely allowing a replacement of fallow land with other crops. Our findings illustrate the importance of combining modelling-methods with direct farmer consultations to attain sensible and comprehensive insights (Kotu et al., 2022; Michalscheck et al., 2018; Nord et al., 2021; Shapiro-Garza et al., 2020).

There were some limitations in this study. Firstly, we did not consult as many women as men and we did not systematically capture whether, and how, men, women or the youth were more or less vulnerable to the different shocks. Secondly, with our project-affiliation, we suspect a desirability bias in the farmer-reported appreciation of the technology packages reported in Section 4.3.2. Respondents might have felt obliged to show their gratefulness or the usefulness of project activities in order to please the project-affiliated researchers and to encourage the continuation of project activities. We noticed a strong appreciation of the material project benefits, since the project-related resilience-strengthening aspect most mentioned ($n = 18/20$) was the provision of inputs by the development project in the scope of their trials. While the ongoing provision of inputs, even just for a small plot of land per household, is a proof of the support and commitment by the project to the farmers, the continued subsidization hindered the observation of actual technology adoption among project beneficiaries. Moreover, especially in the Northern Region of Ghana, many NGOs and projects have been, and continue to be, active, providing agricultural inputs and trainings in a rather un-coordinated manner (Adom, 2015) to the point that farmers are not always able to clearly differentiate who provided what support and with which purpose. In this context, despite making abstract concepts as tangible as possible, it might have been difficult for farmers to truly disentangle the complexity of influences shaping their resilience. However, since our model-based exploration of vulnerability, buffer and adaptive capacity per farm type is based on a careful and conservative triangulation of actual trial data (yields, SOM), technical reports, expert consultations and in-depth interviews with our case study farmers (labour), we judge our model-based results on vulnerability and recovery as solid. Also, the gendered coping strategies were largely unrelated to project activities and unbiased by our project affiliation.

Concerning the transferability of our findings to other smallholder communities in Northern Ghana, we observed differences with other areas within the region: in Nyangua (Upper East Region) for instance, farmers reported that their extensive irrigated dry season gardens and their frequent trade with merchants from Burkina Faso with both agricultural and non-agricultural products, allowed most farmers in the community to generate enough additional income to recover from any shock within one year. For the Upper West Region, Assan et al. (2018) report that a temporary southward migration for labour was a crucial coping strategy of local smallholder farmers in response to dry spells and droughts. In principle, however, we expect similarities, for instance in that LRE households generally evince a relatively small room to manoeuvre with less options to recover than MRE and HRE households (Michalscheck et al., 2018). We also expect HRE households in general to have a large portfolio of agricultural and non-agricultural activities and assets, making them most resilient among the farm types and able to recover quickly after shocks. While our survey results from Duko largely reflect the male perspective and might thus be biased, livestock rearing and sales also stood out as the main coping strategies in times of shock during the Focus Group Discussions that we facilitated in Nyangua (Upper East Region) and Zanko (Upper West Region). Due to the high mortality and theft, investing into livestock seemed to be an effective but expensive insurance for farm households in Northern Ghana. The importance of livestock in times of shock has been reported for smallholder farm systems all over Africa (Acosta et al., 2021), including Kenya (Ng'ang'a et al., 2016; Nyberg et al., 2021; Tittonell, 2014), Zimbabwe (Mutenje et al., 2008), Madagascar (Hänke & Barkmann, 2017), Ethiopia (Tessema & Simane, 2019) and Egypt (Alary et al., 2014). It is important to recognize that farmers have developed their own, often innovative coping mechanisms ranging from an innovative sourcing of poultry feed by trapping termites (Nyangua) to the collection, consumption and sale of a great diversity of wild plants, nuts and fruits – a portfolio of promising ideas and competencies that should not be discounted and are worth further study.

A challenge at community- and possibly at regional-level seems to be, that many farmers aim to be more resilient by doing 'more of the same' by increasing their herd size and expanding their farm land, despite livestock rearing being highly resource consuming (feed, land, labour), frequently unprofitable due to high mortality rates and theft (Amankwah et al., 2012; Kuivanen et al., 2016a) and land becoming increasingly scarce. Similar to descriptions of Hertel et al. (2014), in this context we observe that technologies and techniques that increase the profitability of livestock rearing and crop cultivation, seem to fuel rather than to attenuate the farmers' interest in growing and expanding. In energy economics, it is well studied how efficiency gains through new technologies can be offset by triggering additional demands (Fernández García et al., 2014; Freire-González, 2011; Toroghi & Oliver, 2019; Vélez-Henao et al., 2020) – also denoted as the rebound effect. In the agricultural sciences, we speak of the Jevon's paradox (Jevons, 1866) when intensification intended to reduce pressure on natural resources, such as surrounding lands and forests, has the opposite effect of increased use and degradation of these resources. This phenomenon is well documented for various agroecosystems (Ceddia & Zepharovich, 2017; Ngoma et al., 2021), for water use under efficient irrigation schemes (Sears et al., 2018; Wang et al., 2020) and for energy efficiency actions (Cansino et al., 2019; Sorrell, 2009). We propose that future research gathers further evidence on the community- and landscape-level effects of agricultural intensification (Adhikari et al., 2018), including an analysis on how agricultural expansion versus land sparing impacts ecosystem services and, finally, resilience at farm-household level. Examining how higher-level dynamics support or undermine household-level resilience could provide important additional insights into how smallholder can best prepare for, cope with or recover from shocks.

The livelihoods of smallholder farmers in Northern Ghana are resource intensive and highly coupled with their land assets as their main natural resource base. However, an intensification of resource use at individual or household-level is likely to increase the community- and landscape level pressure on local resources. New questions arise concerning the carrying capacity of local ecosystems and the perspective of sustainable arable farming under scenarios of increasing land scarcity. One way to increase outputs per unit of input is to reduce losses. Preventing post-harvest losses can make a positive difference to farmers' food security and incomes as well as buffer price shocks (Teferra, 2022; Xue et al., 2021). Another loss are preventable constraints on farmers health (Garcia et al., 2020), since their health determines the availability of labour for timely crop cultivation and harvesting, being fundamental to sustain productive farm systems. We conclude that, depending on their resource endowment, their gender and their social network, farmers in Northern Ghana were differently vulnerable and had different coping strategies for shocks such as a severe drought, pest, labour or economic shock. A greater awareness of farm and farmer diversity in terms of livelihoods, challenges and coping strategies, enables improved support for farmers to build more productive, sustainable and resilient farm systems and livelihoods.

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ORCID

Mirja Michalscheck http://orcid.org/0000-0002-5121-6413

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