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Vulnerability and adaptation options to climate change for rural livelihoods – A country-wide analysis for Uganda

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ABSTRACT

Rural households in sub-Saharan Africa earn a substantial part of their living from rain-fed smallholder agriculture, which is highly sensitive to climate change. There is a growing number of multi-level assessments on impacts and adaptation options for African smallholder systems under climate change, yet few studies translate impacts at the individual crop level to vulnerability at the household level, at which other livelihood activities need to be considered. Further, these assessments often use representative household types rather than considering the diversity of households for the identification of larger-scale patterns at sub-national and national levels. We developed a framework that combines crop suitability maps with a household food availability analysis to quantify household vulnerability to climate-related impacts on crop production and effects of adaptation options. The framework was tested for Uganda, identifying four hotspots of household vulnerability across the country. Hotspots were visually identified as areas with a relatively high concentration of vulnerable households, experiencing a decline in household crop suitability. About 30% of the households in the hotspots in (central) southwest were vulnerable to a combination of 3 °C temperature increase and 10% rainfall decline through declining suitability for several key crops (including highland banana, cassava, maize and sorghum). In contrast only 10% of the households in West Nile and central northern Uganda were negatively affected, and these were mainly affected by declining suitability of common beans. Households that depended on common beans and lived at lower elevations in West Nile and central north were vulnerable to a 2 to 3 °C temperature increase, while households located at higher elevations (above 1100–2000 m.a.s.l. depending on the crop) benefited from such an increase. Options for adaptation to increasing temperatures were most beneficial in northern Uganda, while drought-related adaptation options were more beneficial in the southwest. This framework provides a basis for decision makers who need information on where the vulnerable households are, what crops drive the vulnerability at household level and which intervention efforts are most beneficial in which regions.

1. Introduction

Rain-fed smallholder agriculture is an essential source of livelihood for many rural households in sub-Saharan Africa (The World Bank, 2009). While subsistence-oriented crop production is especially important for the food insecure households (Frelat et al., 2016), it is also sensitive to climate change. When assessing climate change impacts on crop production and potential adaptation options for these rural households, studies often focus on individual crops (e.g. Rowhani et al., 2011; Thornton et al., 2009; Traore et al., 2015). Yet, a household's vulnerability depends also on the contribution of other activities to the household's food and income security. Therefore, assessments are needed that identify impacts and adaptation options at the farm and household level while also taking into account non-crop sources of food and income such as livestock and off-farm income (Descheemaeker et al., 2016a). Vulnerability is the degree to which a system is susceptible to an adverse impact and unable to cope with it (Schneider et al., 2007). Vulnerability can be captured by the combination of exposure, sensitivity and adaptive capacity of a system. Exposure to climate change relates to the hazard itself and to the presence of people or

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assets that could be adversely affected (Oppenheimer et al., 2014). Sensitivity relates to the susceptibility of a system to adverse changes and adaptive capacity is the ability of a system to cope with or adapt to adverse changes.

There is an increasing body of literature assessing climate change vulnerability of and adaptation options for smallholder systems in sub-Saharan Africa (Williams et al., 2018). These studies identify how climate change will affect regions, communities, households and livelihoods and which adaptation options are most suitable in which context (Henderson et al., 2018; Traore et al., 2017; Williams et al., 2018). Sub-Saharan African smallholder households can be highly diverse requiring context-specific interventions (Giller et al., 2011). In fact, a recent country-wide analysis of household livelihoods showed that variability between nearby households can be enormous and should be considered when targeting interventions for the most vulnerable (Wichern et al., 2018). Many multi-level assessments that combine the household level with higher levels such as the community (e.g. Asare-Kyei et al., 2017), the district (Oluoko-Odingo, 2011) or the regional level (Herrero et al., 2014) do not account for the local diversity at these higher levels. Rather, information is aggregated and representative household types are used to include household level information in higher level assessments. Hence, an approach is needed that accounts for the variability using household level information without aggregation throughout the multi-level vulnerability assessment. This approach would enable to better quantify the variation in the level of vulnerability of different households in different locations. Such an approach would avoid the results being strongly affected by the type of aggregation that was chosen for, following the 'first simulate then aggregate' principle rather than the often used, but less robust, 'first aggregate then simulate' approach (e.g. Heuvelink and Pebesma, 1999). In our study we aim at tackling these methodological gaps by combining analyses of climate impacts on multiple key crops with the household livelihood context. To this end, we propose a framework for assessing vulnerability at multiple levels from the household to sub-national and national level.

We used Uganda as a case study because of the importance of rain-fed smallholder systems for rural livelihood and because of the diversity in agro-ecology ranging from perennial banana-coffee systems in the humid highlands to dryland pastoral savannah systems in the northeast (Pender et al., 2004; Wortmann and Eledu, 1999). In Uganda rain-fed crop production is an important livelihood activity of rural households for achieving food and income security. Especially the poor and food insecure households tend to be dependent on crop production (Wichern et al., 2017) making them vulnerable to climate change.

Our objective was to determine household vulnerability to climate-related impacts on key crops, identify hotspots of change at the sub-national level and assess possible adaptation options. Using a country-wide household dataset we conduct a spatial analysis through which areas with a high accumulation of vulnerable households are identified and which are likely to be negatively affected by climate change. The following research questions are addressed: How can climate impacts at the crop level be integrated at the household level to identify country-wide household vulnerability? Where are Uganda's hotspots of increased household vulnerability? Which households are vulnerable? And finally, how can household vulnerability in the hotspots be reduced?

In this first presentation of the framework we do not consider climate impacts on non-crop livelihood activities, such as livestock production and off-farm income generation, but our framework has the potential to do so in the future. Instead we illustrate the approach with a simple case in which we use simplified climate scenarios, focus on eight key crops and approximate vulnerability by focussing on changes in crop suitability instead of estimating changes in yields.

2. Material and methods

2.1. Conceptualising vulnerability and introducing the approach

We determined the vulnerability (V) of households based on their exposure (E) and sensitivity (S): $V = f(E,S)$. Exposure was identified based on the suitability of different crops under different climate conditions: current climate (baseline) and different simplified climate scenarios in which monthly temperature and rainfall values changed. The degree of sensitivity of households was determined by the importance of the different crops for household food and income. Combining exposure and sensitivity of the single crops and aggregating them to the household level resulted in a household level suitability indicator. The vulnerability of households was then derived from the change of these household level suitability indicator if climate variables changed. We did not include adaptive capacity in the assessment of vulnerability, but estimated it subsequently by evaluating the effects of different adaptation options in various regions.

In our approach we use a country-wide household survey dataset from Uganda to scale up information on climate impacts and adaptation options from the crop level to the household, sub-national and national levels. Our approach consists of four consecutive steps (Fig. 1): In Step 1, crop suitability maps were generated for eight key crops based on spatially-explicit temperature and rainfall data (see Section 2.2) using the Ecocrop model approach (Ramirez-Villegas et al., 2013). A household level analysis determined the importance of the key crops for household food and income with the household food availability framework of Frelat et al. (2016) using a country-wide household survey dataset (Wichern et al., 2017). Household level suitability was determined from the suitability maps of the key crops and their contributions to household food availability. In Step 2, we conducted a simplified climate scenario analysis using six climate scenarios to capture potential changes in temperature and rainfall and to calculate how crop and household level suitability would change. We classified households based on their household suitability change to estimate household vulnerability.

In Step 3, we identified four vulnerability hotspots with negative household level suitability change, based on the most pessimistic climate scenario. We chose the most pessimistic climate scenario (3 °C temperature increase, 10% rainfall decline) because it included pessimistic projections of both temperature and rainfall trends for Uganda (e.g. Funk et al., 2008; Government of Uganda, 2015; Lyon and DeWitt, 2012; Shongwe et al., 2011). Hotspots were visually identified as areas with a relatively high concentration of vulnerable households, experiencing a decline in household crop suitability. The hotspots were identified by eye using the maps on household suitability change. We identified major differences in livelihood activities between the households that experienced negative, no and positive household suitability change at hotspot level and for different livelihood zones within a hotspot. We also compared patterns along an elevation gradient. In Step 4, we determined potential adaptation options per hotspot and used different adaptation scenarios to identify which of the options were most suitable for which hotspot.

2.2. Data

For the crop suitability analysis we obtained crop specific parameters on temperature and rainfall requirements and on the length of the crop cycle from the R package 'dismo' (Hijmans et al., 2017) and updated them with information from the FAO database Ecocrop (http://ecocrop.fao.org/ecocrop/srv/en/home). We used crop area maps from You et al. (2017) to distinguish between the presence of Arabica or Robusta coffee. Average monthly climate data for minimum, mean and maximum temperature and for rainfall for the period 1970 to 2000 were retrieved from WorldClim (version 2.0, resolution 5 arcmin, Fick and Hijmans, 2017). To distinguish between regions with one and

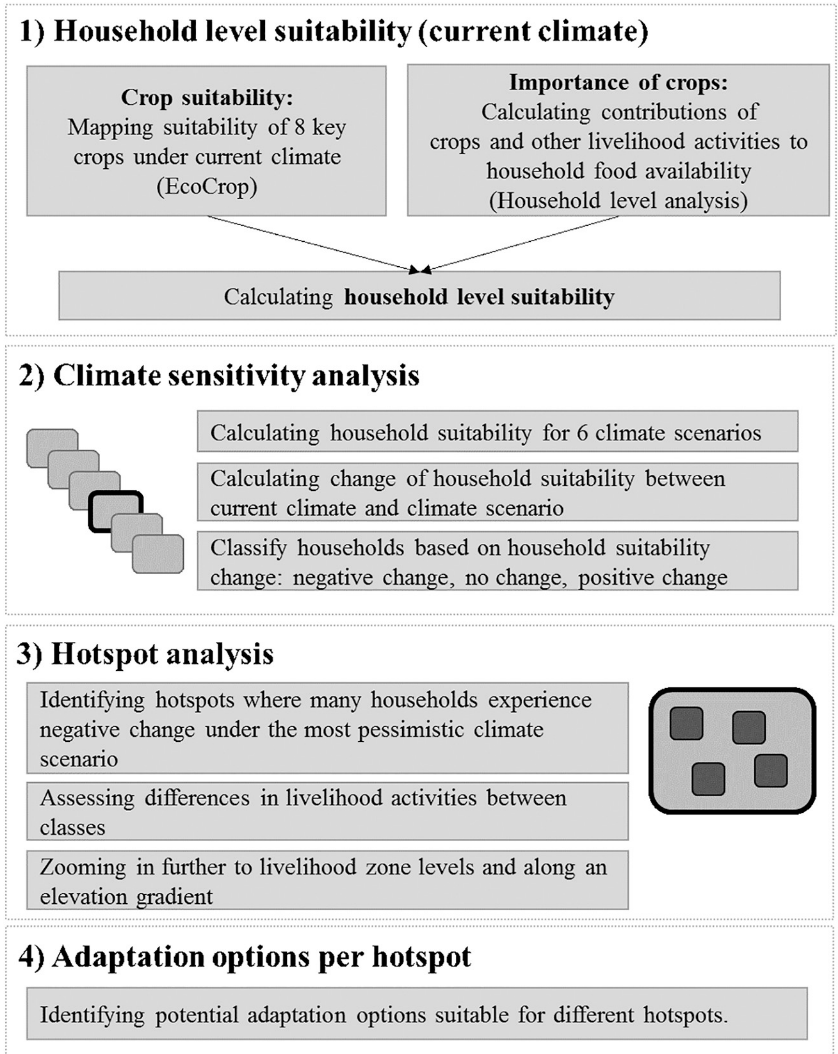

Fig. 1. Schematic overview of the approach, for details see text.

with two seasons, we used the livelihood zone descriptions of FEWS NET (2010).

For the household level analysis, we obtained data on household location, household characteristics, agricultural production and off-farm income from a cross-sectional household survey dataset from the World Bank Living Standard Measurement Study – Integrated Surveys on Agriculture (LSMS-ISA) (Kilic et al., 2015; UBOS, 2011). In total 2671 households were sampled over a 12-month period in 2010/2011. The LSMS-ISA is nationally representative on rural/urban and regional levels. Households were sampled per enumeration area and based on a random selection of enumeration areas per regional strata (The World Bank, 2012).

Since we were interested in the agricultural households, we excluded households without any land holdings. Another twelve households were not geo-referenced and could not be included in the analysis resulting in a final sample of 1927 households. All analyses and mapping were performed in R.

2.3. Uganda as a case study

During the past decades, minimum and maximum temperatures have been rising in Uganda (Kikoyo and Nobert, 2016; Mubiru et al., 2012; Nsubuga et al., 2014) and trends are expected to continue in the near future. Seasonal temperature is projected to increase by > 3 °C (with some differences between the seasons) under the Representative Concentration Pathway (RCP) 8.5 scenario in the coming 80 years. Under the RCP4.5 scenario temperature is projected to increase by 2 °C across Uganda for mid-century and by up to 2.5 °C for end-century (Government of Uganda, 2015; Nsubuga and Rautenbach, 2018). Rainfall projections for East Africa are more uncertain than temperature projections. While global circulation models (GCMs) tend to predict a wetter climate in East Africa towards end-century, regional models suggest that parts of the region become drier (Niang et al., 2014; Patricola and Cook, 2011; Shongwe et al., 2011). For Uganda, under the RCP8.5 and RCP4.5 scenarios changes in annual rainfall of < ± 10% were projected for mid-century with the west and northwest of Uganda becoming slightly wetter, while particularly the southern and central parts becoming drier. A projected increase in rainfall from December to February indicated an extended second cropping season (Government of Uganda, 2015; Nsubuga and Rautenbach, 2018). Trends in heavy rainfall events and droughts in the past decade indicate an increasing frequency of extreme events (Funk et al., 2008; Lyon and DeWitt, 2012), which is likely to continue in the future.

Climate change will affect crop production in Uganda. Maize (*Zea mays* L.) production is expected to be more negatively affected than sorghum (*Sorghum bicolor* (L.) Moench) with considerable yield reductions of up to 45% (Adhikari et al., 2015; Thornton et al., 2010; Thornton et al., 2011). Also common beans (*Phaseolus vulgaris* L.) are expected to experience large yield losses (Thornton et al., 2011), while cassava (*Manihot esculenta* Crantz) production may be less or even positively affected in the region (Jarvis et al., 2012; Lobell et al., 2008; Rosenthal and Ort, 2012). Coffee (*Coffea arabica* L. and *Coffea canephora* Pierre), an important cash and export crop, is expected to experience major losses in yield and coffee bean quality due to temperature increases reducing the extent of suitable areas and increasing the risk for pests and diseases (Adhikari et al., 2015; Jaramillo et al., 2011). Highland banana (*Musa spp., AAA-EA*) already experiences water-constrained conditions and yields may be negatively affected in the future if water stress continues or gets worse in combination with higher temperatures (Adhikari et al., 2015; van Asten et al., 2011).

2.4. Step 1: crop and household level suitability under current climate

2.4.1. Ecocrop model

Crop suitability was calculated for eight crops that are of major importance in Uganda: Highland banana (henceforth 'banana'), common beans (henceforth 'beans'), cassava, Arabica coffee, Robusta coffee, maize, sorghum and groundnut. To calculate crop suitability we used the Ecocrop model, which is a basic mechanistic model that integrates expert knowledge on environmental ranges (from the FAO Ecocrop database, http://ecocrop.fao.org/ecocrop/srv/en/home, accessed 26/11/18) in order to identify the niche of a crop and to produce a crop suitability index as output (values from 0 and 1 with 0 = unsuitable and 1 = highly suitable) (Ramirez-Villegas et al., 2013). The model uses monthly temperature and seasonal rainfall thresholds to identify two ecological ranges for a specific crop (Fig. 2). The absolute range (light grey) is derived from the minimum and maximum absolute temperatures and rainfall amounts at which the crop can grow and beyond which the suitability is zero. The optimum range is derived from the optimum minimum and maximum temperatures and rainfall amounts (dark grey). An additional temperature parameter identifies a monthly minimum temperature below which the crop dies (T_{kill}), defining the location as unsuitable for the crop. If mean temperature or rainfall conditions are between the absolute and optimum thresholds, suitability ranges between 0 and 1 based on a linear function of temperature/ rainfall between the thresholds. If conditions are within the optimum range, suitability equals 1. Overall crop suitability is calculated in three steps: First, temperature suitability is calculated per month within a season. The minimum monthly temperature suitability determines the seasonal temperature suitability. Rainfall suitability is calculated per season. Second, seasonal crop suitability is determined using the minimum value of the seasonal temperature and rainfall suitability indices. Third, if the location has two cropping seasons in a year, overall crop suitability is determined by the mean of the two seasonal crop suitability values. The model is described in detail in SI 1. Crop suitability was calculated for each grid cell.

Livelihood zone descriptions of FEWS NET (2010) were used to select possible starting dates of the seasons (between February and April for cropping season 1 and between July and September for cropping season 2). We calculated seasonal temperature and rainfall suitabilities for each possible starting month for the length of each of the individual crop cycles. We determined the optimal starting month per season and grid cell by selecting the maximum suitability. This way the optimal window for crop cultivation was selected by the model rather than choosing a fixed month. We considered static lengths of crop cycles for both seasons under the current and future climate. In reality, crop cycle lengths are expected to shorten with global warming due to accelerating effects of increased temperature on the phenological development of the crop (Schlenker and Lobell, 2010; Traore et al., 2017), which can negatively affect crop suitability. By contrast, drought (in combination with potassium deficiency) delays bunch development in banana (Taulya, 2013; Taulya et al., 2014). Crop suitability was calculated for current climate and for the different climate and adaptation scenarios (below).

2.4.2. Adjustment of Ecocrop model parameters

The parameters determining the optimum and absolute temperature and rainfall ranges of the crops were retrieved from the R package 'dismo' and updated with information from the FAO Ecocrop database for $T_{KILL\text{-}M}$ for banana. These initial parameters were then adjusted based on input from local experts on the suitability of the different crops in Uganda under current climate and based on information from literature. If experts considered the suitability map to be based on too narrow or too wide temperature or rainfall thresholds, we consulted literature to adjust values to sensible thresholds for Uganda. The length of the crop cycle was derived using the geometric mean of the maximum and minimum crop cycle length reported in the Ecocrop database (Manners and van Etten, 2018) and translated from days to months

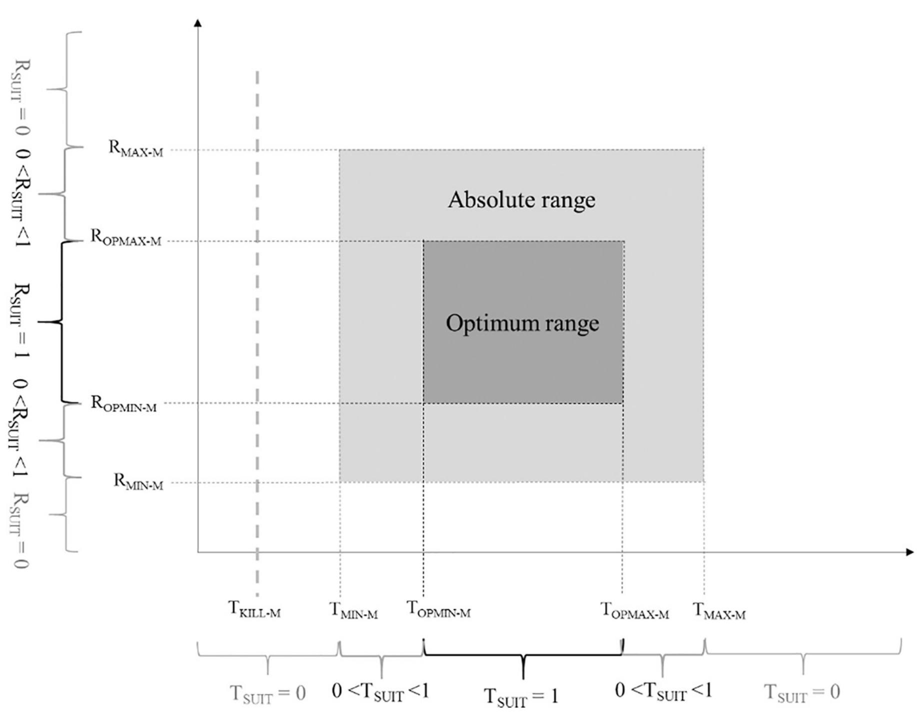

Fig. 2. Ecocrop model, adapted from Ramirez-Villegas et al. (2013). T_{SUIT} = temperature suitability. R_{SUIT} = rainfall suitability. $T_{KILL\text{-}Mi}$ = minimum temperature parameter below which crop dies. $T_{MIN\text{-}M}$ = minimum absolute temperature, $T_{OPMIN\text{-}M}$ = minimum optimum temperature, $T_{OPMAX\text{-}M}$ = maximum optimum temperature, $T_{MAX\text{-}M}$ = maximum absolute temperature. $R_{MIN\text{-}M}$ = minimum absolute rainfall, $R_{OPMIN\text{-}M}$ = minimum optimum rainfall, $R_{OPMAX\text{-}M}$ = maximum optimum rainfall, $R_{MAX\text{-}M}$ = maximum absolute rainfall.

(rounding to nearest integer). For banana and Arabica and Robusta coffee, suitability was calculated for the entire year. SI Table 2 shows the adjusted parameters and the literature used.

2.4.3. Household level analysis

To determine the importance of the different crops for household food and income we used the concept of food availability developed by Frelat et al. (2016). The food availability indicator (FA) estimates the potential food energy available to a male adult equivalent (MAE) household member per day [kcal MAE^{-1} d^{-1}] based on the annual reported agricultural production activities and off-farm income. The indicator uses survey data on directly consumed annual agricultural products [in food energy, kcal a^{-1}] and on indirectly consumed annual food energy potentially obtained from using all the household income to purchase staple food (maize) [in food energy of the staple food, kcal a^{-1}]. Food energy values of the crop and livestock products [kcal] were obtained from the standard product list of the US Department of Agriculture (source: https://ndb.nal.usda.gov/ndb/search/list, accessed 02/07/16) and from the FAO (source: http://www.fao.org/docrep/x5557e/x5557e00.htm#Contents, accessed 02/07/16). By using the medians of reported prices for crops and livestock products we reduced potential effects of erroneous prices in the reported data. We identified the on- and off-farm livelihood activities that contributed to the food availability and expressed them as relative contribution to FA (values from 0 to 1): Crop contribution to FA, livestock contribution to FA and off-farm income contribution to FA. The crop contribution to FA was further subdivided into contributions of banana, beans, cassava, coffee, maize, sorghum, groundnut and other crops to the crop production of FA. Details on this analysis were published in Wichern et al. (2017).

2.4.4. Indicators of household level suitability

To estimate household vulnerability with our conceptual model $V = f(E,S)$, we linked the effects from the exposure E (crop suitabilities dependent on the simplified climate scenarios) to the household sensitivity S (crop contributions to households food availability). The household level analysis was the basis for calculating two indicators of household level suitability: the first indicator, *household level crop suitability, $Suit_{crop}$*, quantified the weighted effect of the suitabilities of the single key crops on the crop production part of household food availability as a combination of exposure and sensitivity:

$$Suit_{crops\ j} = \sum_i (E_{crop\ i,j} \times S_{crop\ i,j}) + 1 \times S_{other\ crops,j} \tag{1}$$

where: $Suit_{crops\ j}$: household level crop suitability of household j, $E_{crop\ i,\ j}$: exposure, derived from the crop suitability of crop i of household j, $S_{crop\ i,\ j}$: sensitivity of household in relation to key crops, derived from the contribution of key crop i to the crop production of FA of household j and $S_{other\ crop\ j}$: sensitivity of household in relation to other crops, derived from the contribution of other crops to the crop production of FA of household j. The contribution of 'other crops' was multiplied by a suitability of 1, because we had no information on the suitability of these other crops.

In the second indicator, *household level suitability, $Suit_{HH}$*, also the other household activities considered in the household level analysis (i.e. livestock production and off-farm income generation) were taken into account:

$$Suit_{HH\ j} = Suit_{crops\ j} \times S_{HH\ crops,j} + 1 \times S_{HH\ other\ activities,j} \tag{2}$$

where: $Suit_{HH\ j}$: household level suitability of household j, $S_{HH\ crops,\ j}$: sensitivity of household in relation to all crops, derived from the contribution of all crops to FA of household j. $S_{HH\ other\ activities,\ j}$: sensitivity of household in relation to other activities, derived from the contribution of other activities (livestock production and off-farm income generation) to FA of household j. Livestock production suitability and off-farm income generation suitability were set to 1 as we had no information on the suitabilities of these activities. Both indicators ranged between zero and one with 1 = highly suitable and 0 = unsuitable.

$Suit_{crops}$ and $Suit_{HH}$ were calculated both for current climate conditions and for simplified climate scenarios in Step 2. Household vulnerability V was then estimated by quantifying the change in household level (crop) suitabilities ($Suit_{crops}$ *and* $Suit_{HH}$) from current climate (base) to the climate scenario:

$$V_{crops\ j} = Suit_{crops,scenario,j} - Suit_{crops,base,j} \tag{3}$$

$$V_{HH\ j} = Suit_{HH,scenario,j} - Suit_{HH,base,j} \tag{4}$$

where: $V_{crops\ j}$: crop level vulnerability of households, derived from the change of household level crop suitability of household j, $V_{HH\ j}$: household level vulnerability, derived from the change of household level suitability of household j, *base*: current climate, *scenario*: simplified climate scenario.

By including the contributions of other crops, livestock and off-farm income as household-specific constants, we were able to reflect the sensitivity of households to climate-related crop suitability changes given the other livelihood activities. Off-farm income generation and livestock production are important livelihood activities for African rural households that help to buffer risks from climate shocks. These activities need to be included to be able to compare households with different compositions of livelihood activities in terms of their sensitivity to crop suitability change. In this way our framework provides a basis to include climate impacts on more crops and non-crop livelihood activities in the future. Including other crops could be a next logical step. Including other activities such as livestock would require additional information, for example on the spatial variability of fodder sources and on the link between climate impacts on fodder sources and subsequent effects on livestock. Since the aim of this study was to demonstrate how climate impacts on crops can be translated to household level vulnerability, we did not include additional crops or activities here, but focused on the key crops for illustration purpose.

2.5. Step 2: simplified climate scenarios and classification of vulnerability

The baseline (current climate) contained spatially-explicit current climate data from WorldClim. The baseline was modified for a set of simplified climate scenarios with a 10% rainfall increase, a 10% rainfall decrease, an increase of monthly mean and minimum temperatures by 2 and 3 °C, and a combination of 3 °C temperature increase and 10% rainfall change, uniform for the entire country and across all the months of the year (Table 1). Scenarios were chosen based on reported projections of temperature increases (Government of Uganda, 2015; Nsubuga and Rautenbach, 2018). As rainfall projections are more uncertain, we included both scenarios with rainfall increase and with rainfall decline. The simplified climate scenario analysis can be compared to a model sensitivity analysis, where it is checked how model outputs vary by varying parameters by a certain percentage. Here, we checked how household vulnerability changed when the climate was changed by a certain percentage (for rainfall) or by a fixed amount (for

Table 1
Simplified **c**limate scenarios. BL = baseline (current climate), +T2/+T3 = Temperature increase by 2 °C/ 3 °C. −R10 = 10% rainfall decline, +R10 = 10% rainfall increase.

	Scenario name	Characteristic of scenario
1	BL (Baseline)	Current climate (WorldClim)
2	−R10	Current climate - 10% rainfall
3	+R10	Current climate +10% rainfall
4	+T2	Current climate +2 °C in monthly minimum and mean temperatures
5	+T3	Current climate +3 °C in monthly minimum and mean temperatures
6	+T3-R10	Current climate +3 °C - 10% rainfall
7	+T3 + R10	Current climate +3 °C + 10% rainfall

temperature).

We classified the households according to their suitability changes V_{crops} and V_{HH}: Class 1: ‘negative change’, if $V_{HH} < -0.05$; Class 2: ‘no change’, if $-0.05 \leq V_{HH} \leq 0.05$; Class 3: ‘positive change’, if $V_{HH} > 0.05$. A threshold of ± 0.05 was chosen to avoid over-interpretation of results for households with minimal change (absolute value < 0.05), given existing uncertainties in the data and approaches in Step 1. Households with negative change were considered ‘vulnerable’, households with no change were considered ‘not vulnerable’ and households with positive change were considered ‘benefitting’.

2.6. Step 3: assessing household vulnerability in the hotspots

We identified four hotspot areas in Uganda, which were visually identified as areas with a relatively high concentration of vulnerable (negative change) households, experiencing a decline in household crop suitability under the simplified climate scenarios (see Section 3.2). The hotspots were identified using the maps in Fig. 6. For these four ‘hotspots’ we assessed how livelihood activities were related to household (crop) suitability change (V_{crops} and V_{HH}). We assessed differences in household suitability changes between hotspots using Kruskal-Wallis test and Wilcoxon rank sum tests. We explored differences in livelihood activities for a) all households in a hotspot, b) households with < 40% off-farm income, and c) households with < 40% off-farm income and > 65% contribution of key crops to the household's crop production of food availability. This was done to interpret correctly the potential bias caused by the household-specific constants on contributions of other crops, livestock and off-farm income included in the framework. Within the four hotspots environmental conditions and farming systems varied, influencing the vulnerability of households to the climate scenarios. To disentangle these effects, we identified patterns of household suitability change V_{HH} for the different livelihood zones (FEWS NET, 2010) and along an elevation gradient within each hotspot.

2.7. Step 4: adaptation options per hotspot

Eight adaptation options were identified for the climate scenario +T3-R10 to assess their effects on household suitability change V_{HH} in the four hotspots (Table 2). Adaptation options were sought in terms of alternative crop varieties, regulation of temperature or water availability in the cropping system and substitution of key crops. Adaptation options included the use of heat-tolerant bean varieties and drought-tolerant maize, the regulation of temperature through shade trees in coffee systems or the regulation of water in banana systems, and the substitution of key crops (beans by groundnut or maize by cassava). Adaptation options were based on existing initiatives and programmes, e.g. the development of heat-tolerant beans varieties to target countries like Uganda by the CGIAR Research Program on Climate Change, Agriculture and Food Security (www.ccafs.cgiar.org/publications/developing-beans-can-beat-heat#.XPFDxhYzapo, accessed 31-05-2019) or the promotion of shade trees in coffee systems (Jassogne et al., 2013) and were based on information from the key crops that were most affected to changes in temperature or rainfall, extracted in Step 3. Adaptation options were mimicked by changing crop parameters in the Ecocrop model, climate data in the climate scenarios, or crop contributions in the food availability calculations.

We identified which adaptation options were most beneficial per hotspot by determining the percentage of households that experienced negative ($V_{HH} \leq$ -0.05) and positive change ($V_{HH} \geq 0.05$) under the climate scenario +T3-R10 in comparison to current climate if they used no adaptation or one of the adaptation options.

3. Results

3.1. Suitability on crop and household level

The crop suitability under current climate was smallest in the northeast and southwest for all key crops except for sorghum (Fig. 3). Rainfall was the main factor that limited suitability of banana, beans, maize, groundnut and coffee in the central southwest and the northeast of Uganda. Temperature limited the suitability for banana, beans, cassava, groundnut, Robusta coffee and sorghum at high elevations, and for Arabica coffee in the northwest of the country (examples in SI Fig. 3).

A 3 °C temperature increase and 10% rainfall decline (climate scenario +T3-R10) showed both positive and negative effects on crop suitability depending on the location and the crop (Fig. 4). For coffee, beans, cassava and maize, the crop suitability was improved when grown at higher elevations ranging from approximately > 1100 m.a.s.l. for cassava to > 2000 m.a.s.l. for beans and Arabica coffee. Increased

Table 2

Adaptation scenarios used under climate scenario +T3-R10 (3 °C increase, 10% rainfall decrease) to evaluate adaptation options for the four hotspots.

Adaptation scenario name		Adjusted parameter	
HeatBe	heat-tolerant bean variety[a]	$T_{OPMAX\text{-}M\ beans} + 4\,°C$	
DroughtMz	drought-tolerant maize variety	$R_{OPMIN\text{-}M\ maize} - 100\ mm\ month^{-1}$	
ShadeCo	shade-tree systems for coffee[b]	$T_{MEAN\text{-}D} - 2\,°C$	
IrrigBa	irrigation of banana systems	$R_{SUIT\ banana} = 1$	
SubstMz	substitute maize by cassava	$CropContr_{cas,\ new} = CropContr_{cas,\ old} + CropContr_{ma,\ old}$ $CropContr_{ma,\ new} = 0$	
SubstBe	substitute beans by groundnut	$CropContr_{gn,\ new} = CropContr_{gn,\ old} + CropContr_{be,\ old}$ $CropContr_{be,\ new} = 0$	
RedMz	reduce maize, increase cassava contribution	$CropContr_{ma,\ new} =$	if $CropContr_{ma,\ old} \leq 0.2$: $CropContr_{ma,\ old}$ if $CropContr_{ma,\ old} > 0.2$: 0.2
		$CropContr_{cas,\ new} =$	if $CropContr_{ma,\ old} \leq 0.2$: $CropContr_{cas,\ old}$ if $CropContr_{ma,\ old} > 0.2$: $CropContr_{cas,\ old} + CropContr_{ma,\ new}$
RedBe	reduce beans, increase groundnut contribution	$CropContr_{be,\ new} =$	if $CropContr_{be,\ old} \leq 0.15$: $CropContr_{be,\ old}$ if $CropContr_{be,\ old} > 0.15$: 0.15
		$CropContr_{gn,\ new} =$	if $CropContr_{be,\ old} \leq 0.15$: $CropContr_{gn,\ old}$ if $CropContr_{be,\ old} > 0.15$: $CropContr_{gn,\ old} + CropContr_{be,\ new}$

$T_{OPMAX\text{-}M\ i}$: model parameter for maximum optimum temperature of crop *i*; $T_{MAX\text{-}M\ i}$: model parameter for maximum temperature of crop *i*; $R_{OPMIN\text{-}M\ i}$: model parameter for minimum optimum rainfall of crop *i*; $T_{MEAN\text{-}D\ i}$: monthly mean temperature of crop *i* (in data); $R_{SUIT\ i}$: rainfall suitability for crop *i*; $CropContr_{cas}$: contribution of cassava to the crop production of food availability, $CropContr_{ma}$: contribution of maize to the crop production of food availability, $CropContr_{be}$: contribution of beans to the crop production of food availability, $CropContr_{gn}$: contribution of groundnut to the crop production of food availability. [a]parameter from: www.ccafs.cgiar.org/publications/developing-beans-can-beat-heat#.XPFDxhYzapo. [b]parameter from Jassogne et al. (2013) and Vaast et al. (2006).

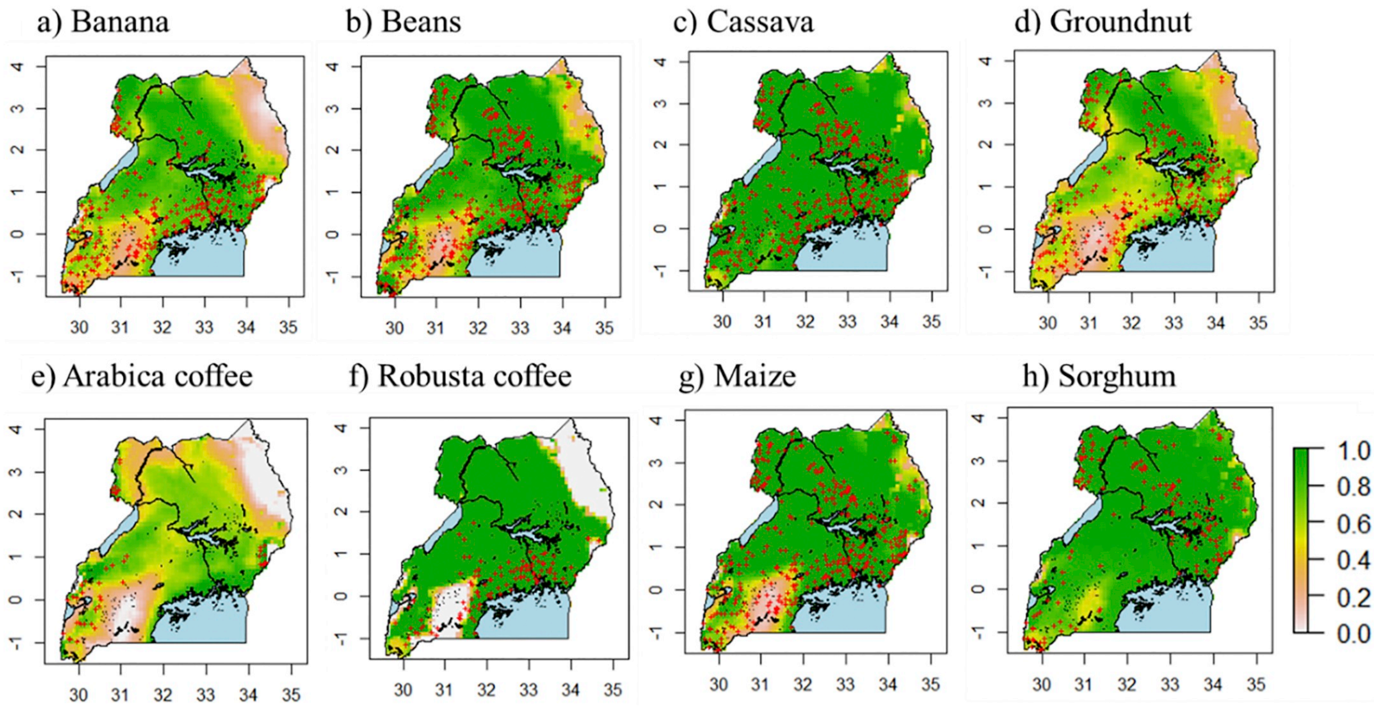

Fig. 3. Crop suitability under current climate for eight key crops based on thresholds of monthly temperature and seasonal rainfall using the Ecocrop model. A suitability score = 1 means highly suitable, a suitability score = 0 means not suitable. The red + represent the households with the particular crop present on their farm. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

temperature had negative effects on crop suitability for beans, cassava and Arabica coffee in the north. Reduced rainfall constrained banana, cassava, maize and sorghum in the southwest.

Under current climate household level suitabilities ($Suit_{crops}$ and $Suit_{HH}$) were > 0.7 for the majority of the households. Only in the central southwest suitabilities were < 0.7 due to rainfall constraints (SI Fig. 4). Climate scenarios including a rainfall decline resulted in negative household suitability change (V_{crops} and V_{HH}) for some households, while rainfall increase resulted in positive V_{crops} and V_{HH}. Effects on temperature were mixed with some households experiencing positive V_{crops} and V_{HH}, while others experienced negative V_{crops} and V_{HH} (Fig. 5). Under a temperature increase by 2 or 3 °C, more negatively affected households occurred in the northwest and central north compared to other regions, while positively affected households occurred at

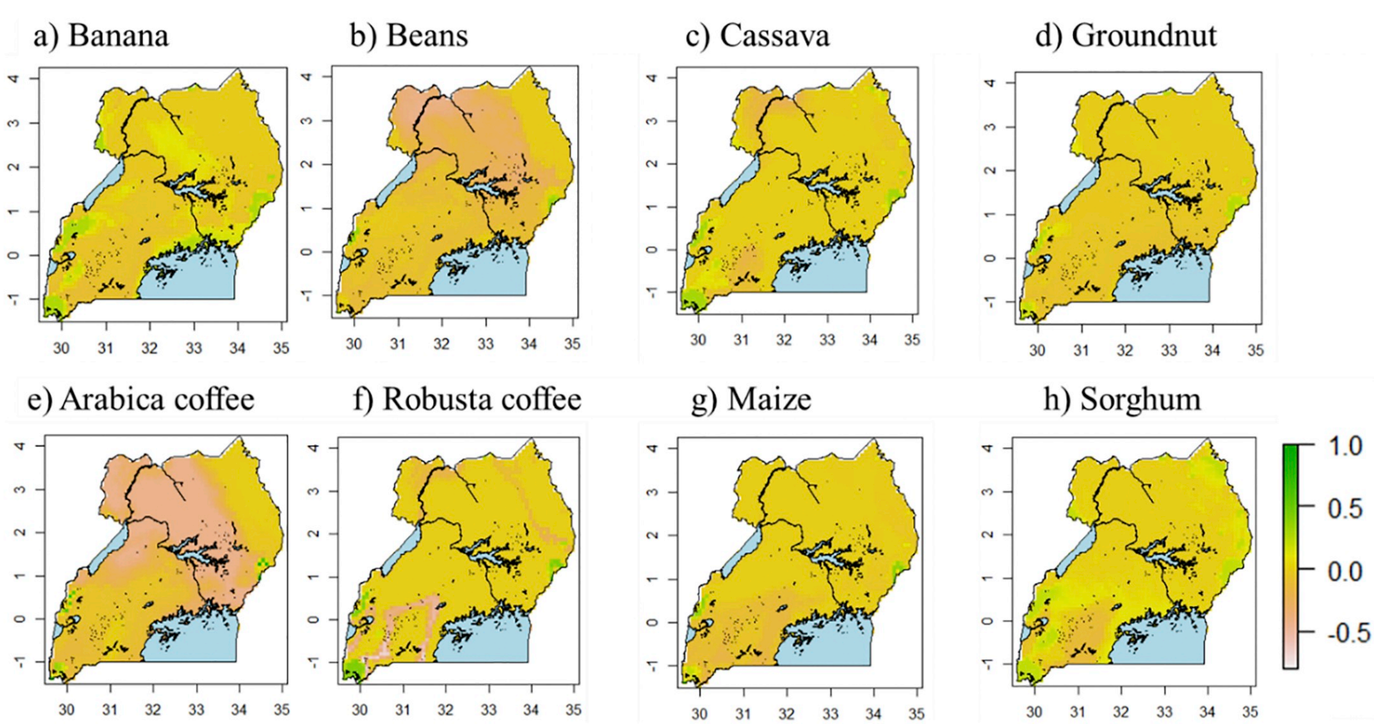

Fig. 4. Change in crop level suitability under climate scenario +T3-R10 compared to current climate (maps show difference = crop level suitability$_{+T3\text{-}R10}$ − crop level suitability$_{base}$).

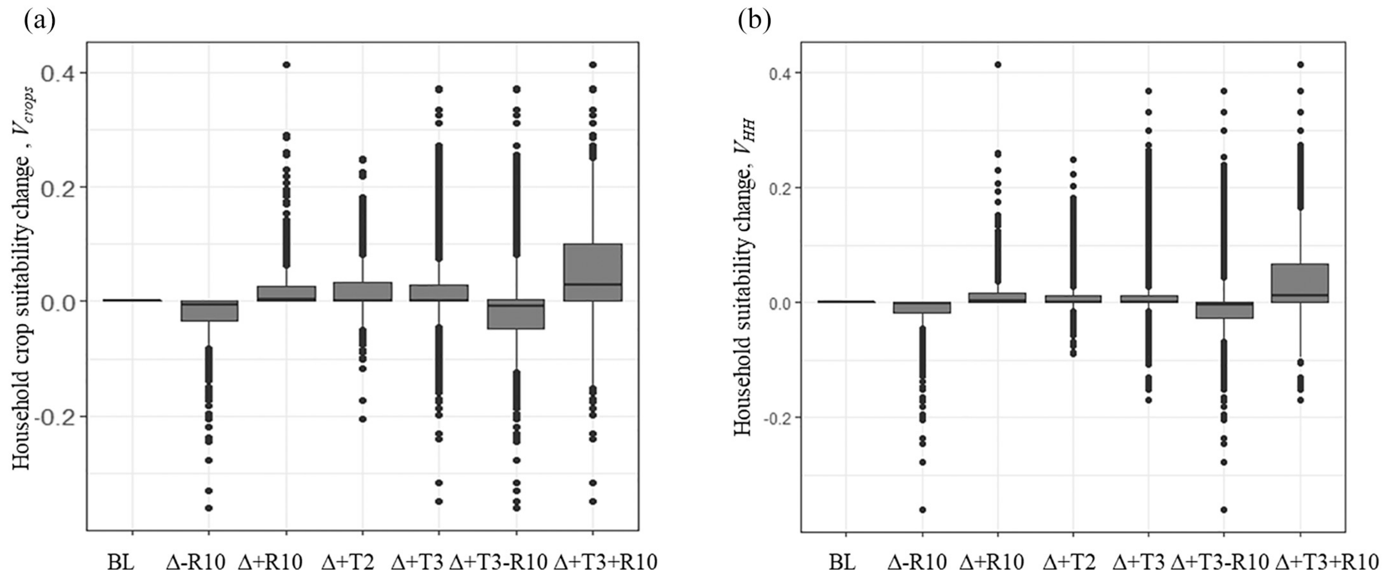

Fig. 5. a) Household crop suitability change (V_{crops}) and b) household suitability change (V_{HH}) under six simplified climate scenarios for all households across Uganda.

higher elevations and along Lake Victoria (Fig. 6). Under a uniform 10% rainfall increase, household suitability improved in Uganda's south, while under a 10% rainfall decline household suitability declined as well in the same area compared to the baseline.

For the further analyses we focused on the simplified climate scenario of combined effects of 3 °C temperature increase and 10% rainfall decline (scenario +T3-R10) because it included pessimistic projections of both temperature and rainfall trends for Uganda (e.g. Funk et al., 2008; Government of Uganda, 2015; Lyon and DeWitt, 2012; Shongwe et al., 2011).

3.2. Differences across four hotspots

We selected four hotspots where a relatively high concentration of vulnerable households occurred that were negatively affected under the climate scenario +T3-R10: West Nile in the northwest, central north, southwest and central southwest (SI Fig. 5). On average, households in West Nile tended to be less negatively affected than in the other three hotspots and households in Southwest Central tended to be more negatively affected than the households in the two northern hotspots (SI Table 6).

V_{crops} was negatively related to beans contribution to the household's crop production in West Nile and central north and positively related to banana contribution in West Nile (SI Fig. 7). Correlations between V_{crops} and contributions of key crops were less strong in the southwest and central southwest. Rather, more localised trends seemed to have influenced V_{crops} in these two hotspots.

We classified households according to their change in household suitability, V_{HH} (negative change, no change, positive change). While in the southwest and central southwest about 30% of households were classified under negative change, it was only about 10% of households in West Nile and central north (see Fig. 8, scenario "NoAdap"). Households with no change were characterised by large contributions of off-farm income and livestock to food availability (Fig. 6a) and of other crops contributing to the crop production of food availability (Fig. 6b top). This was a direct result of the analysis framework in which off-farm income, livestock and other (non-key) crops were considered not affected by the climate scenarios. To separate relevant livelihood activities from the effects of the framework, we looked at a subset of households in which the eight key crops played a major role (Fig. 6b bottom). For these households (West Nile: 84 households representing 42% of the sample population in that hotspot, central north: 91 households representing 36%, southwest: 177 households representing 65%, and Central southwest: 236 households representing 65% of the sample population) the contribution of key crops differed per hotspot and class: In West Nile, households with positive change were particularly the ones where banana contribution was larger. These households were located in the southern part of West Nile. Here temperatures were lower (due to higher elevations) and farming systems included coffee and banana. In contrast in the northern part of West Nile, households depended more on annual crops and more households experienced negative change. In central north beans were less important and maize and cassava more important for the households with no change in V_{HH} compared to the households with negative V_{HH}. In central southwest benefitting households depended more on cassava and less on maize and households with no change had more Robusta coffee and less banana. In southwest differences in crop contributions were small between households with positive compared to those with negative change, which was probably because local differences were hidden at this aggregation level.

A comparison of V_{HH} in relation to elevation and livelihood zone revealed that differences in positive and negative changes in West Nile and southwest were strongly related to elevation and subsequently to livelihood zones (SI Fig. 8). While households in the higher elevations (livelihood zones UG16, UG35) tended to experience positive change, households in the lower elevations (livelihood zones UG07, UG15, UG23) tended to experience negative change. These patterns were not observed in central north and central southwest where the elevation gradient was much smaller and for livelihood zone UG39 (southwest).

3.3. Identifying suitable adaptation options per hotspot

The eight adaptation options (Table 2) were chosen based on the simplified climate scenario and hotspot analyses. Heat-tolerant bean varieties were tested because of their importance in the farming systems in the northern hotspots, two areas sensitive to temperature increase. Drought-tolerant maize varieties and irrigation of bananas were tested because of the impact of declining rainfall in the southern hotspots. Substitution of maize/ beans by cassava/ groundnut was chosen as an adaptation option because of the larger ranges in minimum and maximum rainfall/ temperature of cassava/ groundnut compared to maize/ beans, respectively. Sensitivity of coffee to climate change was addressed by testing the use of shade trees to regulate temperature.

A clear differentiation in the effectiveness of different adaptation

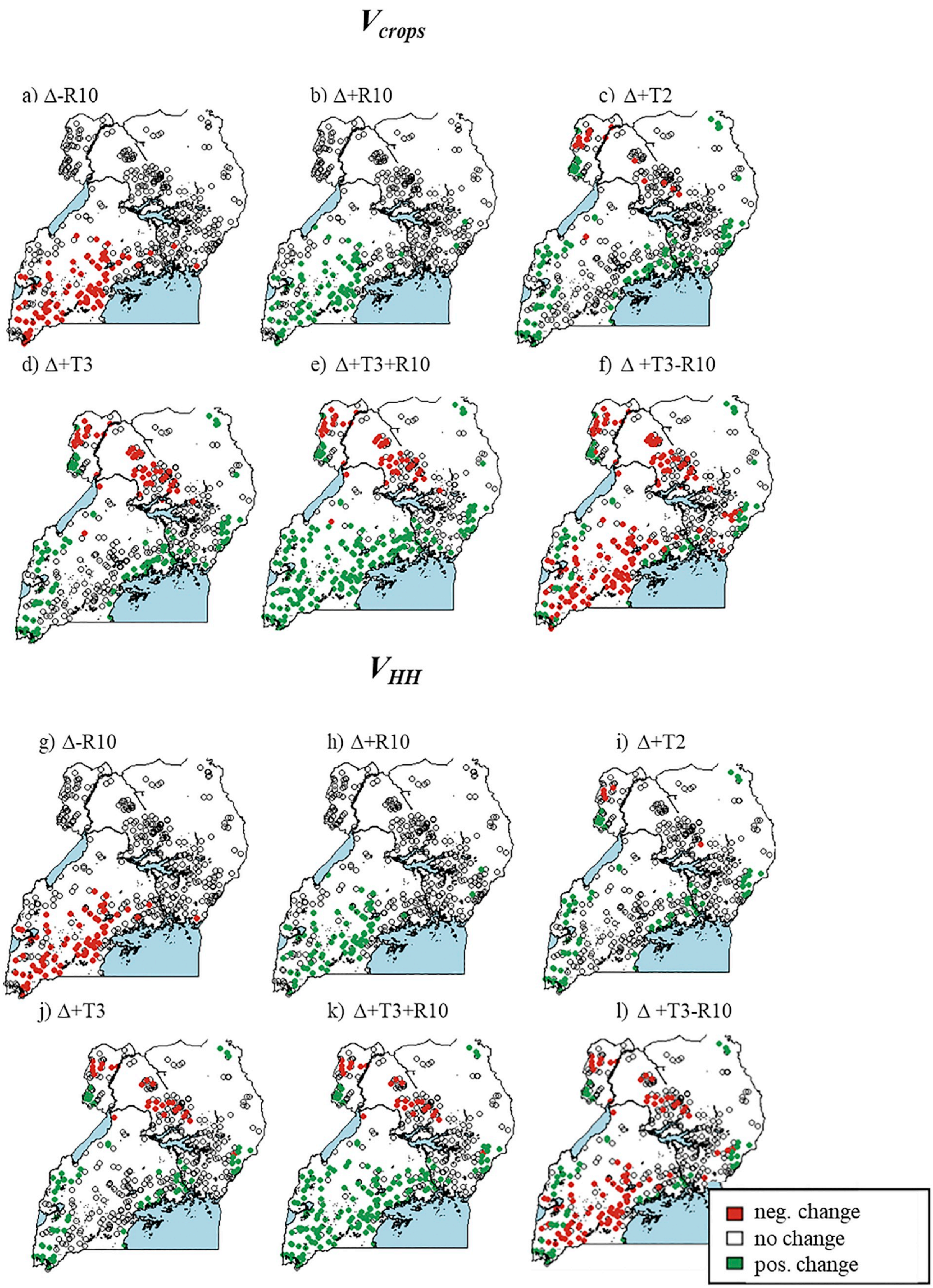

Fig. 6. Household (crop) vulnerability represented by household level crop suitability change (V_{crops}, a-f) and household level suitability change (V_{HH}, g-l) under six simplified climate scenarios: Difference between scenario -R10 and current climate (a, g); +R10 and current climate (b, h); +T2 and current climate (c, i); +T3 and current climate (d, j), +T3 + R10 and current climate (e, k); +T3-R10 and current climate (f, l). -10% = 10% monthly rainfall decline, +R10 = 10% monthly rainfall increase, +T3 = 3 °C monthly minimum and mean temperature increase. Negative change: V_{crops} or V_{HH} < -0.05. Positive change: − V_{crops} or V_{HH} > 0.05. No change: *-0.05* ≤ V_{crops} or V_{HH} ≤ 0.05.

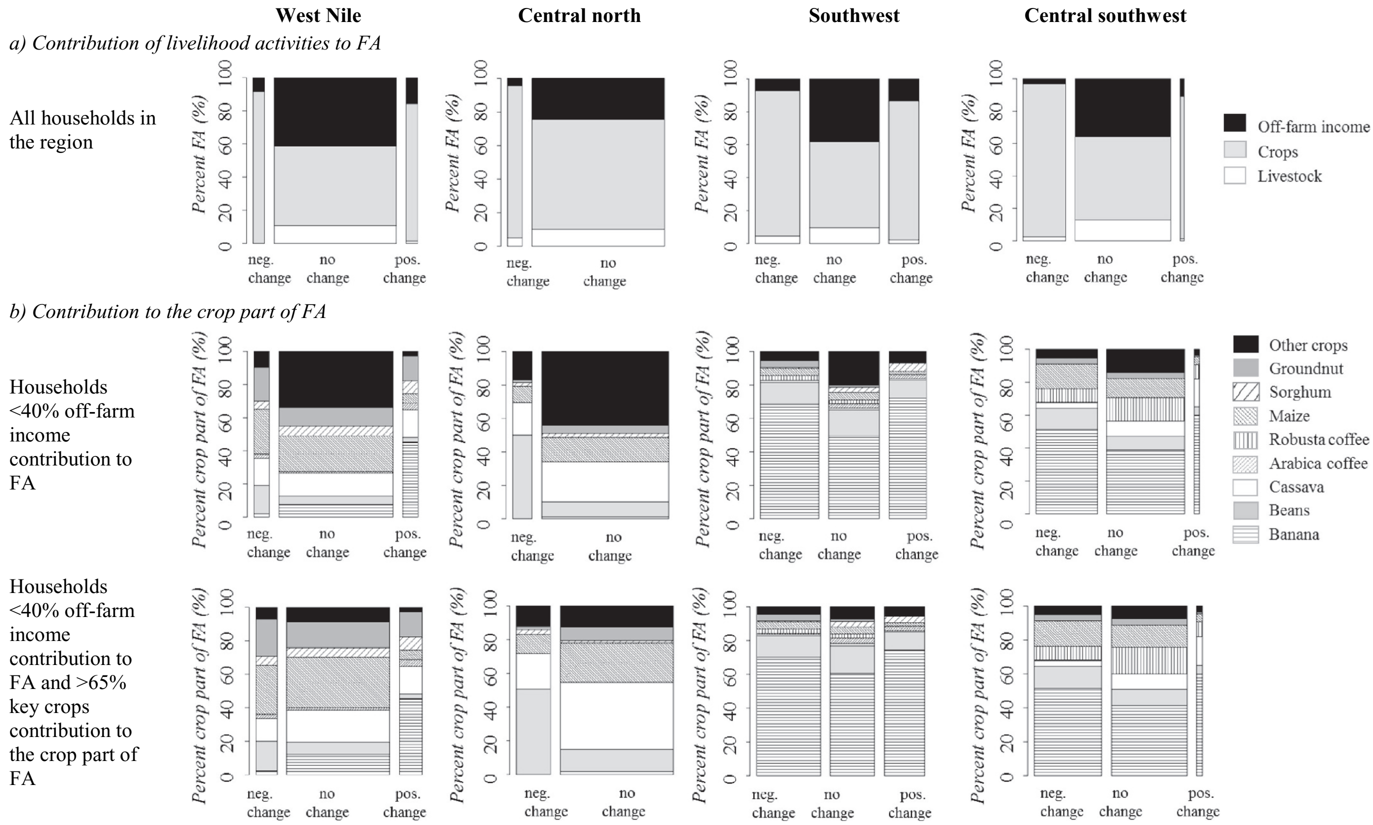

Fig. 7. Livelihood activities (a) and crops (b) contributing to food availability (FA), classified by household level suitability change (neg. change = negative change; no change; pos. Change = positive change) from baseline to scenario +T3-R10 per hotspot (3 °C increase and 10% rainfall decrease compared to baseline). Width of bar represents percentage of households in class. Information on household numbers in SI Table 9.

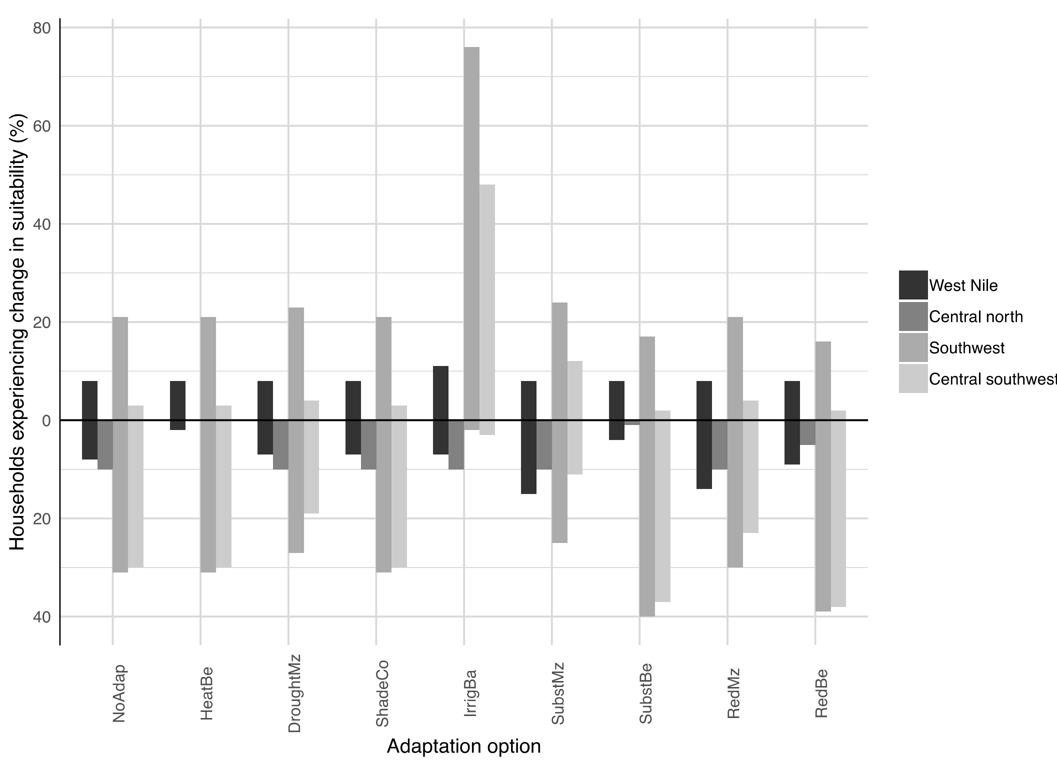

Fig. 8. Percentage of households per hotspot experiencing a negative (bars facing down from the horizontal line) or a positive (upward bars) change in household level suitability due to climate change (3 °C increase and 10% rainfall decrease) compared to current climate and for different adaptation options (For explanation of adaptation options see Table 2).

options by hotspot was visible for central north, southwest and southwest central (Fig. 8). In central north the most effective adaptation options were to introduce heat-tolerant bean varieties (*HeatBe*) or to reduce beans and increase groundnut contribution (*RedBe*). These two adaptation options reduced the number of negatively affected households across all major livelihood zones (SI Table 10B). In southwest and central southwest improving the water availability for banana (*IrrigBa*) had the most positive effect on V_{HH}. In central southwest introducing a drought-tolerant maize variety (*DroughtMz*) or reducing maize production and substituting it by cassava (*SubstMz*) improved the amount of negatively affected households slightly, but effects differed per livelihood zone (SI Table 10D). Not all households in a hotspot benefitted from the adaptation options in the same way. While at hotspot level, some adaptation options led to improvement, at the household level diverse effects were noted. For example, the reduction of beans and simultaneous increase of groundnut (*SubstBe*) in central north reduced the number of households negatively affected from 25 to five households. Of these 25 households three households remained negatively affected, because the improvement from the adaptation measure was insufficient to compensate for the negative effects caused by temperature increase and rainfall decline. In addition, two new households became negatively affected under the adaptation scenario *SubstBe* because groundnut had a lower suitability score than beans at those two locations.

4. Discussion

4.1. Crop and household suitability and the vulnerability hotspots in Uganda

We identified four hotspots of household vulnerability in Uganda (West Nile, central north, southwest and central southwest) driven by the change in suitability of different key crops and their importance in the farm livelihood. The results show how agro-ecological conditions and farm livelihood strategies combine to create a mosaic of possible climate change impacts across Uganda. Promising adaptation options match this mosaic, thereby creating a nuanced overview of what households can do in which hotspots to adapt to climate change. The results indicate that under some agro-ecological conditions (e.g. at higher elevations) climate change may improve crop productivity.

Crop level suitability under current climate for the eight key crops (banana, beans, cassava, coffee Arabica, coffee Robusta, groundnut, maize and sorghum) was constrained more by rainfall than by temperature, particularly in southwestern Uganda. Results match with observations that banana production, which is an important crop in Uganda's southwest, is currently constrained by water availability (van Asten et al., 2011). Our suitability assessments for banana resembled findings from a similar analysis, which revealed that moisture deficits are likely to retard banana growth if rainfall declines (Sabiiti et al., 2018). Suitability of sorghum resembled existing coarser maps (Ramirez-Villegas et al., 2013). Compared with earlier research (Jassogne et al., 2013), our Arabica coffee suitability map was more favourable and was determined by rainfall rather than temperature. Jassogne et al. (2013) used a different approach, in which the crop parameters of the suitability model were trained based on present occurrence locations of coffee (Bunn, 2015). By contrast, we used universally applicable crop suitability thresholds that were adjusted based on expert knowledge. This approach also explains why some of the crops were present in areas where suitability was small (e.g. *Robusta* coffee, beans or groundnut). This can be related to a missing link or missing input variable in the Ecocrop model (e.g. effects of temperature-rainfall interactions on suitability or of soil conditions on suitability), but can also be related to economic or cultural preferences of smallholders for a certain crop despite small suitability of that crop. Cassava was highly suitable across Uganda and was only little negatively affected under the climate scenario (3 °C temperature increase, 10% rainfall decline) supporting observations that cassava can be an important crop for climate change adaptation (Jarvis et al., 2012).

Household level suitability change under the simplified climate scenarios was particularly affected by temperature increase in northern Uganda and by rainfall changes in southwestern Uganda. The households in the southern hotspots would be hit hardest if future climate becomes drier, as projected by the Government of Uganda (2015), since they already live under drought-prone conditions (Mulinde et al., 2016; Rojas et al., 2011). Households experiencing negative household suitability change in the north depended more on beans, while the link of suitability change to crop dependency was more diffuse in the southwest and central southwest. Many crops in the southern hotspots were already limited by rainfall conditions under current climate explaining the larger proportion of households being vulnerable in the southern hotspots. Surprisingly, our household vulnerability analysis did not reveal hotspots of vulnerability in Uganda's northeast, an area regularly identified as one of the most vulnerable regions in Uganda with large food insecurity and high risk of crop failure due to extended dry spells and droughts (Nakalembe, 2018; Netherlands Space Office, 2018). Possible reasons for this observation include that most sampled households in that area depended on sorghum, a crop that is more robust to dry conditions than many of the other key crops. In addition, droughts and intra-seasonal dry spells were not directly captured in this framework. Further, the density of household observations in this area was small probably leading to insufficiently capturing patterns in this area. Finally, our framework did not account for socio-economic factors that might be more relevant in determining vulnerability and particularly adaptive capacity of households in that area (Jordaan, 2014) such as poverty and food insecurity.

4.2. Adaptation options to reduce vulnerability to climate change in the hotspots

In West Nile and central north temperature-related adaptation options showed positive effects on household level suitability, while in the southwest and central southwest drought-related adaptation options were most effective. Measures to deal with drought such as securing water resources and cultivating drought-tolerant crops are already adopted by farmers in southwestern Uganda (Cooper and Wheeler, 2017) and the potential positive effects of cultivating heat-tolerant bean varieties under future climate change have been demonstrated for Uganda (CIAT, 2009). We developed a short-list of possible adaptation options as examples, while water conservation and heat regulation options can be manifold and need to fit the local context. Eventually, adaptation options must fit the socio-ecological niche of the households in order to be feasible (Descheemaeker et al., 2016b) and a supportive institutional setting is needed that allows adaptation options to be effective and efficient (Agrawal and Perrin, 2008; Clay and King, 2019; Unks et al., 2019). This requires that these multi-level (country-wide) assessments are linked to contextualised in-depth studies within hotspots assessing who can benefit from which potentially suitable adaptation options. Adaptation options that go beyond the crop level were not explored in this framework, yet they have the potential to decrease household vulnerability to climate change by reducing the household's dependency on crop production.

4.3. Integrating climate change impacts on key crops to identify household vulnerability

We combined crop suitability maps of eight key crops with a household level analysis on the importance of these crops for household food availability. Our framework enabled to identify hotspots of vulnerable households across Uganda (*where* they are), determine the crops per hotspot that drive household vulnerability (*why which* households are vulnerable), and test relevant adaptation options per hotspot (*what* could work *where*). Different adaptation options play out differently in different locations and for different households. As such this framework is a first step towards quantifying the potential benefits of adaptation options in limiting negative effects of climate change at different locations. The approach contributes to existing literature as it systematically links from crop to household to sub-national (hotspots) levels thereby enabling to identify vulnerability at the household level and taking climate effects on a diverse set of crops into account. It can add to existing work that assesses risks of crop loss due to droughts or other climate impacts (such as efforts like the SUM Africa project of Netherlands Space Office (2018)) by pointing out which households might be at greatest risk due to their dependency on most affected crops. The underlying household level analysis provides a basis for further exploration to understand household vulnerability in relation to other (minor) crops and to livestock.

The framework does not account for the role of climate risk and its influence on poverty dynamics (Hansen et al., 2019) and does not consider changes in the socio-economic context that are unrelated to climate change. It does not take account of interacting effects of rainfall and temperature, seasonal differences within a year (e.g. if the first season is drier and the second season wetter) and changes in the length of the cropping cycles under climate change. Crop parameters on temperature and rainfall determine the crop suitability, while in reality crop suitability is also influenced by other parameters such as soil conditions. These are limitations to the framework that may result in overestimating crop suitabilities in some locations, for example for banana in northern Uganda. We used average monthly rainfall and temperature changes, while increasing night temperature, heat waves, dry spells, floods and other extreme events also influence crop production. We used average lengths of cropping cycles, although in reality the length differs between varieties. A 'whole-household' perspective that takes into account the effects of climate change on other livelihood activities such as livestock production and off-farm income generation was beyond the scope of this study, but this framework has the capacity to do so in the future. The zoomed-in vulnerability analysis focused on the T3-R10 scenario – the most pessimistic scenario among the ones tested. This resulted in a pessimistic vulnerability assessment. Yet, results give a good indication on why, where and how different households would be affected by temperature increase and/or rainfall decline, which is becoming a reality for many households in Uganda (Lyon and DeWitt, 2012; Muthoni et al., 2018; Nsubuga et al., 2014).

Although we did not use climate change models in this exercise, this framework can be linked to GCMs in order to get a finer-grained picture on potential climate change effects across Uganda, which would increase the usability of results for policy advice. However, since the main objective here was to test the feasibility of the approach, and understand the underlying links between crop suitability changes and household level vulnerability, we used simplified climate scenarios. These scenarios make the uncertainty in climate predictions explicit, thus revealing the location of vulnerability hotspots for a range of possible changes in rainfall and temperature and their combination.

Besides these limitations the framework provides a basis for further analyses, for example by including climate change effects on other crops, livestock and off-farm income and by assessing the effects of various adaptation options on household income and food security. Effective adaptation options were identified based on positive effects in household level suitability change. However, households will only adopt options if these benefit the households' goals, for example to achieve food and/or income security. Even if future yields of crops such as maize may be lower than today due to smaller suitability, households might still cultivate them if they provide sufficient income. Crop prices are sensitive to climate impacts (Wossen et al., 2018). Thus, even if a switch from maize to cassava or to other crops seems logical from a crop suitability perspective, price dynamics of these crops influence a farmer's decision on which crops to cultivate. Within this framework we can adjust price and production values for specific crops to (re)calculate income and food availability and get an idea what the effect of different adaptation options would be on household food security or income. Finally, when using other coherent large datasets of farm household characterisation data (e.g. the RHoMIS effort, Hammond et al., 2017), this framework can perform more detailed analyses per hotspot and better quantify effects beyond the simple food availability indicator (e.g. on nutrition, poverty, and other food security indicators). It thereby enables linking climate change impacts on agricultural (crop) production to household indicators of poverty and food insecurity, which can provide further in-depth insight into the adaptive capacity of households.

5. Conclusions

This research integrated climate change impacts on key crops at the household level to identify household vulnerability across Uganda. The framework enabled to identify areas of vulnerable households, determine the crops contributing most to household vulnerability and test which intervention efforts could be effective where, considering the heterogeneity of household livelihood activities. It thereby provides a useful basis for decision makers that need information on where which kind of resources should be allocated. For example, in the northern hotspots in Uganda the framework suggests that efforts should focus on heat-regulating interventions, while in the southern hotspots water conservation measures are more relevant.

With progressing climate change, spatially-explicit vulnerability assessments will become increasingly important for governments and other institutions that aim at reducing vulnerability and improving food security of rural households in sub-Saharan Africa. This framework provides a firm basis, while it can be further advanced by including non-crop livelihood activities, such as livestock production and off-farm income, in the assessment of household vulnerability to climate change. Such a 'whole-farm' assessment can also be linked to indicators of underlying food insecurity and poverty that influence adaptive capacity and thereby vulnerability.

Declaration of Competing Interest

None

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Appendix A. Supplementary data

Supplementary data to this article can be found online at https://doi.org/10.1016/j.agsy.2019.102663.

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