Pathogen and pest risks to vegetatively propagated crops in humanitarian contexts: Toward a national plant health risk analysis for Cameroon and Ethiopia

Romaric A. Mouafo-Tchinda[1,2,3*], Berea A. Etherton[1,2,3*], Aaron I. Plex Sulá[1,2,3], Jorge Andrade-Piedra[4], Kwame Ogero[5], Bonaventure A. Omondi[6], Margaret A. McEwan[7], Paul M. Tene Tayo[8], Dieudonné Harahagazwe[9], Mihiretu Cherinet[10], Setegn Gebeyehu[11], Louise Sperling[12], and Karen A. Garrett[1,2,3*]

[1] Plant Pathology Department, University of Florida, Gainesville, FL, USA
[2] Global Food Systems Institute, University of Florida, Gainesville, FL, USA
[3] Emerging Pathogens Institute, University of Florida, Gainesville, FL, USA
[4] International Potato Center (CIP), Lima, Peru
[5] International Potato Center (CIP), Mwanza, Tanzania
[6] Alliance of Bioversity International and CIAT, Cotonou, Benin
[7] International Potato Center (CIP) Africa Regional Office, Nairobi, Kenya and Wageningen University and Research, Netherlands
[8] Biotechnology Center, University of Yaoundé, Yaoundé, Cameroon
[9] International Potato Center (CIP), Yaoundé, Cameroon
[10] International Potato Center (CIP), Hawassa, Ethiopia
[11] International Potato Center (CIP), Addis Ababa, Ethiopia
[12] SeedSystem, Sherman, CT, USA
* corresponding author(s)

R. A. Mouafo-Tchinda and B. A. Etherton made equivalent contributions

Emails, respectively: rmouafotchinda@ufl.edu*, betherton@ufl.edu*, plexaaron@ufl.edu, j.andrade@cgiar.org, k.ogero@cgiar.org, b.omondi@cgiar.org, margaret.mcewan08@gmail.com, martialtene@gmail.com, dharahagazwe@gmail.com, m.cherinet@cgiar.org, setegn.gebeyehu@cgiar.org, sperling@seedsystem.org, karengarrett@ufl.edu*

ORCID IDs, respectively: 0000-0003-1343-4820, 0000-0002-4127-4484, 0000-0001-7317-3090, 0000-0001-7617-0506, 0000-0002-5141-6781, 0000-0001-9711-5645, 0000-0001-8510-0526, 0000-0002-8895-5615, 0000-0002-1337-1041, 0000-0002-5947-7175, 0000-0003-4610-1934, 0000-0002-2134-2638, 0000-0002-6578-1616

Keywords: humanitarian crises, expert knowledge elicitation, banana, cassava, potato sweetpotato, network analysis,

Funding: USAID Bureau for Humanitarian Assistance (BHA), CGIAR Seed Equal Research Initiative, USDA Animal and Plant Health Inspection Service (APHIS)

Acknowledgements

We appreciate support from USAID Bureau for Humanitarian Assistance award number BHA 720BHA22IO00136 and the CGIAR Seed Equal Research Initiative; we thank all donors and organizations which globally support its work through their contributions to the CGIAR Trust Fund. We also appreciate support from USDA Animal and Plant Health Inspection Service (APHIS) Cooperative Agreements AP21PPQS&T00C195 and AP22PPQS&T00C133. The opinions expressed in this article are those of the authors and do not necessarily reflect the view of the USAID BHA or USDA APHIS. We also appreciate the contributions of participants in the expert knowledge elicitation, including experts who chose to remain anonymous and Gashaw Belay Alemu, Getachew Asefa, Atnafua Bekele, Tesfaye Abebe Desta, Astride S. Djabou Mouafi, Levai Lewis Dopgima, Demis Fikre, Dereje Haile, Wakene Hambisa, Denberu Kebede, Idriss Kouam, Bililign Mekonnen, Esmelealem Mihretu, Lionnel Nkamagne, Atsede Solomon, Yitagesu Tadesse, Lemlem Teklemedhin, Lemme Tessema, and Manamno Workayehu.

Abstract

Cameroon and Ethiopia face humanitarian crises that disrupt the production of key food security crops like banana and plantain, cassava, potato, and sweetpotato. In this study, we address seed degeneration in these crops, the reduction in planting material quality due to the accumulation of pathogens and pests. We consider the context of humanitarian crises, with the goal of developing an ongoing 'national plant health risk analysis', in this case to inform decisions about mitigating seed degeneration. We analyzed cropland density maps and applied network centrality metrics to identify locations that are candidates for disease and pest management and surveillance in Cameroon and Ethiopia. We used expert knowledge elicitation and global trade data to map pathogen and pest movement risks and characterize trade of crop-specific commodities and planting materials. We identified specific locations that may be important for pathogen and pest spread in in Cameroon and Ethiopia, given their roles in the cropland network, and the reported presence of pathogens and pests. This national plant health risk analysis can inform regional and national surveillance and management strategies and provide a baseline for more in-depth studies in Cameroon and Ethiopia. We discuss strategies for ongoing improvement of a national plant health risk analysis, to inform decision-making in the humanitarian sector for designing on-the-ground actions to avoid unintentional spread of pathogens and pests during agricultural recovery interventions.

1 Introduction

1.1 The importance of root, tuber, and banana crops for low-income countries and challenges for seed health

In the face of climate change and increasing natural and human-driven disasters, staple food crops like roots, tubers, and bananas (RTBs) are essential for food security (Scott, 2021; Thiele et al., 2017). RTBs are widely consumed, with a market value of US$339 billion annually, providing nutrients for food-insecure populations in low-income countries (Petsakos et al., 2019; Scott, 2021). RTBs are vegetatively propagated, with planting material ('seed') that includes suckers (banana, (*Musa* spp.) , stakes (cassava *Manihot esculenta*), tubers (potato, *Solanum tuberosum*) , and vines (sweetpotato, *Ipomoea batatas*). Vegetative propagation increases the risk of seed degeneration, or the build-up of pests and pathogens in planting material, and can facilitate the unintentional spread of pests and pathogens through seed trade or replanting (Gibson & Kreuze, 2015; Jacobsen et al., 2019; Thomas-Sharma et al., 2017; Thomas-Sharma et al., 2016). Seed degeneration can be exacerbated by informal trade if growers unknowingly spread pests and pathogens to other growers through casual or unregulated seed trade (Scott, 2021; Sperling & Almekinders, 2023; Sperling et al., 2020). Informally traded seed of RTB crops (i.e., planting material obtained from neighbors, local markets, uncertified seed producers or traders), along with on-farm saved seed, is the primary seed source for growers in low-income countries and has little or no official (formally regulated) phytosanitary control (Delaquis et al., 2020; Sperling & McGuire, 2010; Thomas-Sharma et al., 2016). Formal seed trade (i.e., seed obtained from certified governmental distributors, private seed companies, or NGOs) has the potential to offer certified seed free of specific pathogens or pests. Yet, the relatively high price of formal seed coupled with factors such as limited access, preference for certain varieties, diverse use of vegetative parts of plants, cultural traditions, or simply lack of infrastructure or awareness of seed health concerns, can deter growers, even when formal

97 sector seed may be available. In this study, we focus on seed systems of RTB crops in Cameroon and
98 Ethiopia, countries that rely on informal seed trade and on RTB crops for income generation and food
99 security (Hirpa et al., 2010; OCHA, 2023a). Informally traded seed has some advantages for growers – it
100 may be readily available and affordable- but this analysis focuses on disease risks due to informal seed
101 trade as well as commodity trade. By mapping national and cross-border movement of seed of RTB crops,
102 we identify regions which may be at risk for pathogen introduction through trade flows – including risk
103 during and after disasters. These analyses are part of an ongoing 'national plant health risk analysis'
104 proposed for these crops, and implemented in a baseline version in this paper.

105 **1.2 Ongoing disasters and humanitarian needs in Cameroon and Ethiopia**

106 Disaster plant pathology addresses how disasters influence plant disease dynamics, through
107 increasing human migration, infrastructure destruction, aid distribution, and creating more suitable
108 environments for plant diseases (Etherton et al., 2024). Some disasters like droughts, floods, forest fires
109 and hurricanes have direct impacts on plant health, through the spread of pathogens and pests, especially
110 impactful if the species are new introductions to the region. Political unrest, conflicts, and wars can
111 indirectly affect crop health, through damaged agricultural infrastructure and reduced human capacity
112 and attention to crop health. Disasters can lead to the accumulation of pathogens and pests, triggering
113 epidemics and exacerbating food insecurity in vulnerable communities (Etherton et al., 2024).

114 Cameroon and Ethiopia face many types of humanitarian challenges, motivating the analysis of
115 these country's seed systems in the context of disaster plant pathology. In Cameroon, humanitarian crises
116 include natural disasters that affect nearly every part of the country, such as flooding, deforestation,
117 desertification/droughts, and landslides (Bang, 2021; Bang & Balgah, 2022) **(Figure 1)**. Human-driven
118 challenges include armed conflicts like the Boko Haram insurgency in the Far North region, the separatist
119 conflict in the Northwest and Southwest regions, and societal challenges related to the influx of refugees

from the Central African Republic in the East, Adamawa and North regions (Bang & Balgah, 2022; Mbah et al., 2023). The agricultural communities in these areas are affected by these compounding crises, diminishing already limited resources. Growers are abandoning their fields due to these crises, with the risk of food shortages affecting their families (FAO, 2021a, 2021b; OCHA, 2023a). Cameroon hosts more than 450,000 refugees and asylum seekers annually, and the demand for humanitarian aid continues to grow (Macrotrends, 2023; OCHA, 2022). However, humanitarian access remains a major challenge due to administrative obstacles, insecurity instilled by armed groups, and infrastructure damage (ECPHAO, 2023).

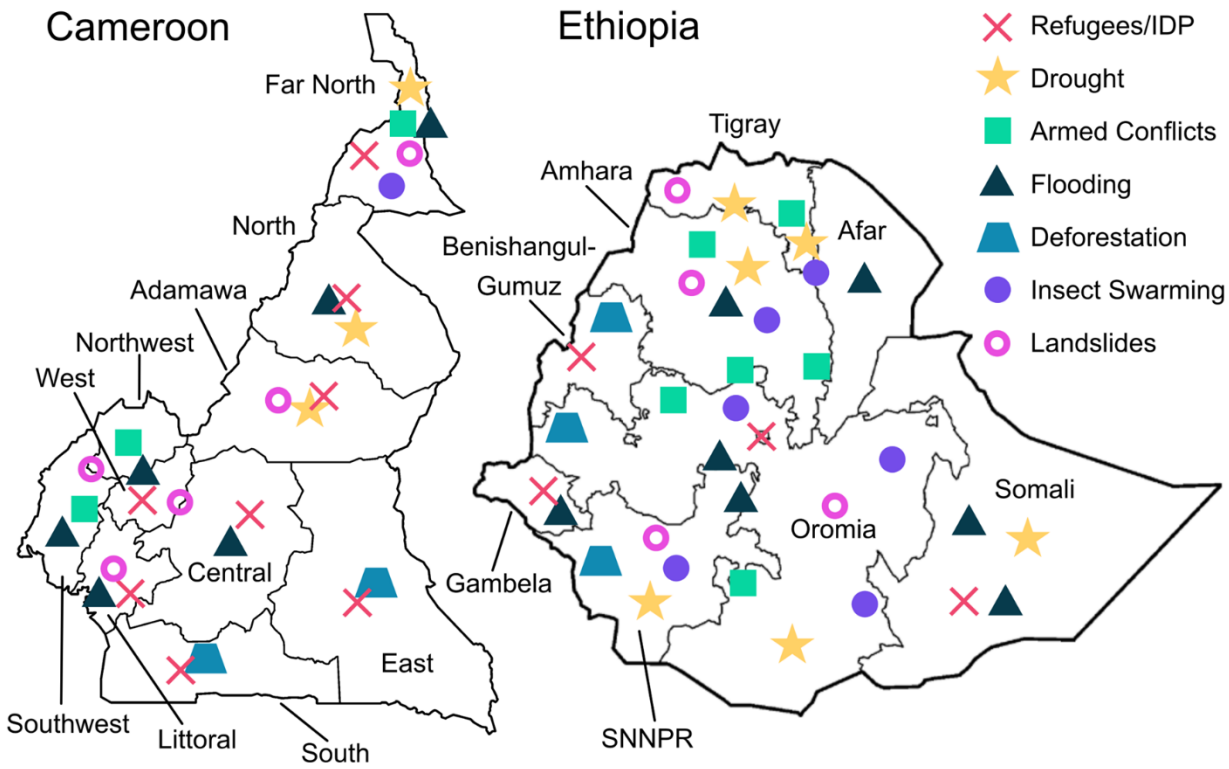

Figure 1. Maps of Cameroon and Ethiopia indicating representative types of disaster and humanitarian issues such as major conflicts that affect agricultural production. For example, red 'X's represent refugee issues and/or internally displaced people (IDP). These icons are placed approximately and do not reflect exact locations or every reported disaster. Data adapted from Bang and Balgah (2022), IOM (2023), and Raleigh et al. (2010). The map of Ethiopia reflects the administrative boundaries described in 2022; SNNPR: former Southern Nations, Nationalities, and Peoples' Region.

Humanitarian crises in Ethiopia are often associated with drought, floods, armed conflicts, pest outbreaks, and political instability, of which drought is a main factor reducing agricultural production and increasing malnutrition among the affected communities (Alasow et al., 2023; CDP, 2023; Wubaye et al., 2023) **(Figure 1)**. The frequency of droughts affecting cropland in Ethiopia has nearly doubled in the last 50 years (Alasow et al., 2023). The severe drought that began in 2020 continued into 2023, with five failed rainy seasons in many parts of the country (Alasow et al., 2023; CDP, 2023; Wubaye et al., 2023). Ethiopia has experienced several armed conflicts, including the Tigray civil conflict. Disputes between the Ethiopian military and the militias in the Amhara region have created a dire situation for more than five million people across these regions, causing growers to migrate to neighboring states or countries (CDP, 2023). The compounded effects of climate shocks, armed conflicts, and related displacement, continue to drive humanitarian needs, and more than 20 million people required food assistance in 2023 (OCHA, 2023b). In addition to a loss of assets and planting material, a significant proportion of growers affected by multiple disasters are unable to save or manage seed effectively, causing a staggering demand for seed supply as part of the emergency response. Affected populations may also need other types of emergency recovery support to resume agricultural activities, including access to fertilizers, pesticides, farm tools, and cash. Given these acute and chronic stresses, Ethiopian farmers have been major recipients of seed aid on an ongoing basis for over 40 years (McGuire & Sperling, 2008; Sperling et al., 2007).

1.3 The need for analysis of crop health risk to inform humanitarian aid interventions

The humanitarian imperative goes beyond saving lives and addressing immediate needs for food, water, health care, and shelter; it also aims to establish responses that foster livelihood recovery and enhance resilience over both the short and medium term (Hunt et al., 2018; USAID, 2022). After disasters occur, the relevance of agricultural interventions depends on factors such as coordination with planting seasons, the availability of resources (e.g., access to arable land, labor, seed), the willingness of farmers to plant, and basic security considerations (e.g., whether growers can safely sow and harvest in a given

period) (Sperling, 2008). A key priority is ensuring access to pathogen- and pest-free seed, through regulated interventions or direct distribution. This priority should include, at a minimum, quality seed of known low levels of pathogens and pests, and of crop varieties and seed types that meet farmer preferences (Nduwimana et al., 2022; Sperling et al., 2022).

For organizations planning emergency aid, or planning development assistance, there is often limited information available to assemble a 'national plant health risk analysis' that includes the range of pathogens and pests that threaten crop health, along with their potential spread through planting materials and other means, even when studies of plant health have addressed specific species in specific locations. For example, in Cameroon, there have been targeted studies of diseases and pests of RTB crops, such as weevils, nematodes, sigatoka, and banana bunchy top disease in banana (Fogain et al., 1998; Ngatat et al., 2022; Okolle et al., 2009), cassava viruses, cassava whitefly, cassava root rot, cassava green mite, cassava root mealybug, cassava anthracnose, and cassava bacterial blight on cassava (Doungous et al., 2022; Poubom et al., 2005; Tize et al., 2021), and potato tuber moth, aphids, potato viruses, leaf miners, bacterial wilt, and late blight on potato (Deloko et al., 2021; Konje et al., 2019). In Ethiopia, studies have also been conducted on the incidence and spread of some important diseases and pests of potato and sweetpotato, such as potato bacterial wilt (Tessema & Seid, 2023), viral diseases of sweetpotato (Buko et al., 2020; Tesfaye et al., 2011) and sweetpotato weevil (Beyene, 2015). However, we are not aware of publications evaluating the general risk of geographic spread of these pathogens and pests in Cameroon and Ethiopia. Knowledge of key pathogens and pests is important for ensuring both seed quality and availability of crop varieties with useful resistance genes, for cases where resistance is available. When there is the risk of introducing a new pathogen or pest to a country or region, zero tolerance for the presence of this new threat in seed is an important goal. However, the source and health status of seed are often unknown and seed regulatory systems may not function sufficiently to provide assurance of seed quality along the whole delivery chain. The common lack of systematic and current

176 pathogen and pest information, that could support a national plant health risk analysis, highlights the
177 importance of rapid risk assessment tools that identify regions likely to be important in pathogen and pest
178 spread, target economically important pathogens and pests, and assess the potential role of informal
179 trade in pathogen and pest spread (Carvajal-Yepes et al., 2019; Thomas-Sharma et al., 2017; Xing et al.,
180 2020). This information can help in identifying risks for consideration in emergency seed assistance and
181 planning longer-term agricultural development strategies.

182 **1.4 The objectives and approaches of this study**

183 This paper introduces elements of a national plant health risk analysis and discusses how these can be
184 built on in ongoing analyses and improvements. The analysis is designed to be useful for supporting
185 decision-making about crop protection and healthy seed systems in humanitarian settings. We use two
186 complementary approaches in rapid risk assessment and mitigation for decision-support of pathogen and
187 pest management. These tools, when used before, during, or after disasters, can help humanitarian
188 groups prioritize seed assistance strategies and mitigate disease and pest threats to agricultural
189 communities. The first approach is cropland connectivity analysis, which provides maps of the likely role of
190 geographic locations in the spread of pathogens and pests, based on the landscape of crop host
191 availability for crop-specific pathogens and pests (Keshav et al., 2024; Margosian et al., 2009; Xing et al.,
192 2020). Cropland connectivity analyses can consider a wide range of parameter values to account for the
193 dispersal kernels of different pathogens and pests. They can be targeted to an individual pathogen or pest
194 species, or provide broad summaries across pests and diseases, as we apply them here. Locations likely to
195 act as hubs or bridges for pathogen or pest movement are highlighted in the analysis, and these are
196 candidate priorities for management interventions and seed testing (Andersen Onofre et al., 2019;
197 Andersen Onofre et al., 2021; Buddenhagen et al., 2017; Buddenhagen et al., 2022). The second approach
198 is expert knowledge elicitation, which provides information on current RTB seed systems based on crop
199 experts' knowledge and identifies gaps in domain knowledge (Andersen Onofre et al., 2021; Thomas-

Sharma et al., 2017). Together these two approaches can provide rapid risk assessments and a baseline for more detailed follow-up studies as resources allow.

The objectives of this study are to 1) identify locations likely to be important for pathogen and pest spread in potato and sweetpotato, given the locations' roles in each country's network of crop host availability, 2) evaluate disease and pest risk in Cameroon and Ethiopia using expert knowledge elicitation, and 3) identify potential risks to the spread of pathogens and pests through informal seed trade and trade of crop commodities. We expand these analyses for Cameroon to include two more major food security crops: banana (also including plantain) and cassava. In a linked study, we evaluated the risk for potato diseases in Ethiopia with a focus on bacterial wilt (Etherton et al., 2025). Here our goal is to provide an initial draft of a 'national plant health risk analysis' for these RTB crops in Cameroon and Ethiopia that generates actionable insights for decision-making by humanitarian organizations, growers, RTB researchers, and national programs, with the potential to inform regulatory policies and guide on-the-ground practical actions. This study was built on insights gained from our previous capacity needs assessment surveys among humanitarian organizations in Cameroon, the Democratic Republic of Congo, Ethiopia, Haiti, Mozambique, Bangladesh, and Madagascar (Andrade-Piedra et al., 2023; Canney-Davison et al., 2023). This baseline national plant health risk analysis characterizes the geographic regions with the potential to play important roles in epidemics, the pest and pathogen communities present in these regions, and the potential for pathogen and pest movement through planting material – to support disaster-specific response strategies that protect crop health.

2 Methods

The analyses were implemented with code available in GitHub at https://githu.com/GarrettLab/Mouafo-Tchinda-Etherton-et-al-2024. Versions of these analyses are part of the ongoing development of the Rapid Risk assessment for Mitigation of plant pathogens and pests (R2M) toolbox (garrettlab.com/r2m/).

223 2.1 Cropland connectivity for host-specific pathogens and pests

224 We analyzed cropland connectivity to map locations likely to be important in outbreaks of host-
225 specific pathogens and pests in Cameroon and Ethiopia. Cropland connectivity analyses evaluate potential
226 epidemic or invasion networks of crop-specific pathogens and pests in a region, based on host availability,
227 and evaluate each crop production location in terms of how important the location is likely to be in
228 spread through the network (Margosian et al., 2009; Xing et al., 2020). In separate crop-specific analyses,
229 we used 2017 harvested area (ha) raster files for banana and plantain, cassava, potato and sweetpotato
230 from the MapSPAM database (International Food Policy Research, 2020). Cropland within each country
231 and in the immediate neighboring countries (±0.5° latitude and longitude) were included in the network
232 analyses. Locations (individual pixels within the cropland raster maps) with harvested areas greater than
233 zero were retained as network nodes, and a gravity model was used to evaluate the relative likelihood of
234 dispersal between each pair of nodes (Jongejans et al., 2015). The gravity model describes the "pull" of
235 two masses on each other; the more cropland a region has, the higher "gravitational pull" it has across a
236 network. In epidemiological applications, the gravity model reflects how greater host availability at a node
237 can make it a more important inoculum source and also make inoculum that reaches the node more likely
238 to reach the host.

239 Gravity models also incorporate the role of distance, where movement is more likely between
240 closer locations (nodes). We used the gravity model $M_i M_j d_{ij}^{-\beta}$, where M_i and M_j represent the harvested
241 crop area of two nodes i and j. The first gravity model used the inverse power law dispersal kernel $d_{ij}^{-\beta}$,
242 where d_{ij} represents the distance between nodes i and j, and β indicates the likelihood of pathogen
243 movement across that distance (Andersen Onofre et al., 2021; Xing et al., 2020). We also used the gravity
244 model $M_i M_j e^{-\gamma d_{ij}}$, with the dispersal kernel based on the negative exponential model, where γ indicates
245 the likelihood of pathogen movement. The distance between two locations (nodes) was calculated using

the terra package in R (version 1.7-71) (Hijmans et al., 2022), a geographical spatial data analysis package. The relative likelihood of pathogen movement between two nodes i and j for $\beta = 1$ is higher than for $\beta = 2$; similarly, movement for $\gamma = 1$ is more likely than for $\gamma = 2$. We use both the inverse power law and the negative exponential models, each commonly used to model pathogen and pest dispersal, across a range of β and γ values, in sensitivity analyses and to explore a range of scenarios.

For each crop individually, the importance of each node in epidemic/invasion networks was evaluated using a cropland connectivity risk index (CCRI) as described by Xing et al. (2020), using the geohabnet package in R (version 4.3.2) (Keshav et al., 2024), a package for evaluating habitat connectivity. The CCRI was defined as the weighted sum of four network metrics, to capture a range of potential roles a location (a pixel that includes the crop) may have during an epidemic or pest invasion. The network was first built using the gravity model as described above, where nodes are pixels that include the crop, and link weights are the relative likelihoods of pest or pathogen movement. The four metrics describing the importance of each node were 1) betweenness centrality, indicating a node's role as a pathway between other nodes in a network (bridge nodes), 2) node strength, indicating its connection to other nodes in the cropland network, 3) the sum of a node's nearest neighbors' node degrees, indicating how connected a node's closest neighbors are, and 4) eigenvector centrality, which accounts for both quantity and quality of links in the cropland network. The CCRI used here is the sum of these four centrality metrics, weighted by 1/2, 1/6, 1/6 and 1/6, respectively. This weighting emphasizes betweenness centrality, to highlight the significance of each node as a bridge or pathway for the spread of pests and pathogens to other nodes. At this point in the analysis, the resulting risk map represents the weighted sum of these centrality metrics for one combination of parameter values.

We repeated the analysis of the gravity model network and the four network centrality metrics across a range of parameters, to capture a wide range of movement patterns for various pathogens and

269 pests. We developed the individual risk maps for β = 0.5, 1.0, and 1.5, and γ = 0.05, 0.1, 0.2, and 0.3., and
270 took the mean at each geographic pixel across the results from all parameter combinations, to provide a
271 general CCRI for each location. That is, the value mapped at each location in the general summary map is
272 the weighted mean of centrality metrics (the CCRI) averaged across all parameter combinations in the
273 sensitivity analysis. Higher CCRI scores indicate locations that are more likely to play an important role in
274 an epidemic or invasion based on host availability, pathogen or pest dispersal, and proximity to other
275 crop production.

276 **2.2 Expert knowledge elicitation**

277 We developed surveys for use in expert knowledge elicitation for Cameroon and Ethiopia to
278 capture the knowledge of RTB experts currently working in the field. Considering the growing but still
279 limited databases available to support seed system responses in humanitarian situations (see
280 https://seedsystem.org/field-assessments-action-plans/), especially to support strategies for RTB crop
281 health, the goal was to assemble current expert knowledge in a useful framework to support decision-
282 making. Expert knowledge elicitation can be used to assess the risk of pest and pathogen spread through
283 seed in areas vulnerable to humanitarian emergencies, and to help countries formulate management
284 strategies against invasive crop pests and pathogens.

285 The first stage of survey development was to review the content of the country- and crop-specific
286 surveys with the organizing team to make sure they were appropriately matched to the situation in each
287 country. The surveys focused on RTB pathogens and pests causing high yield loss, with potentially
288 important impacts on vulnerable human populations. In Cameroon, four surveys covered banana,
289 cassava, potato and sweetpotato. Similarly, two surveys were designed for experts in Ethiopia, focusing
290 on potato and sweetpotato. Surveys were deployed using Google Forms (Vasantha Raju & Harinarayana,
291 2016). Crop-specific experts who had some insights into seed systems participated in one-day workshops

292 in November 2022 in Yaoundé, Cameroon, and in March 2023 in Addis Ababa, Ethiopia. In Cameroon, we
293 recruited 18 experts for cassava, 13 for potato, 10 for banana and 7 for sweetpotato. In Ethiopia, we
294 recruited 20 experts for potato, and 9 for sweetpotato. Experts known through previous collaboration
295 with CGIAR and the University of Florida were selected based on their experience with RTB crops,
296 representing governmental organizations, the private sector, NGOs, National Agricultural Research and
297 Extension Systems (NARES), and CGIAR centers (IITA, CIP, and Alliance Biodiversity-CIAT). Across crops
298 and locations, 60 to 78% of participating experts identified as seed system experts in Cameroon or seed
299 system/breeding experts in Ethiopia. Anonymized information about the experts' experience in each state
300 or region and each crop, along with all crop-specific responses, are available upon request. Participating
301 experts completed the surveys individually, for the crop for which they had expertise. Experts were first
302 asked to provide their years of experience in each region or state in their country of expertise. In each
303 survey, experts were then asked to identify the major pests and diseases, identify the informal exchange
304 routes for seed in the country and with neighboring countries, estimating crop-system specific
305 parameters.

306 Answers from experts were compiled and organized by administrative regions or states in each
307 country. In Ethiopia, state boundaries have now changed, but the regional states in March 2023 were
308 Tigray, Afar, Amhara, Benishangul-Gumuz, Somali, Oromia, Gambela, Southwestern, Southern Nations,
309 Addis Ababa, Dire Dawa and Harari. An initial list of key pathogens and pests was drawn from previous
310 studies carried out in both countries, and based on preliminary discussions with the organizing team. The
311 pathogens and pests reported in the expert knowledge elicitation to be present in regions or states were
312 compiled, and visualized using polar bar plots using the R package ggplot2, a graphical visualization
313 package (version 3.3.6) (Wickham, 2016). Experts were not asked to identify the absence of pests and
314 pathogens, so it should be noted that a lack of reports on a pest or pathogen's presence in a region or
315 state does not necessarily imply absence, only that experts were not aware of its presence. We summed

316 the total years of experience reported by experts in each region or state and used the log transform of this
317 sum as a proxy for relative confidence in the reports for a region or state. For both countries, pest and
318 pathogen community maps were created for potato and sweetpotato, and for Cameroon also for cassava
319 and banana. Note that an important caveat for comparison of locations is that locations with less crop
320 production tend to have less attention by experts, so lower expert experience in a region in a sense
321 represents 'lower sampling effort'; that is, regions and regional states where experts have less experience
322 will tend to have lower numbers of pathogen and pest species reported. Visualizations for each crop
323 indicate whether at least one expert reported each pest or pathogen in each region or state, and the
324 corresponding relative confidence for the region or state based on the total years of expert experience
325 for the region or state.

326 ## 2.3 Within-country informal seed trade in Cameroon

327 Experts in Cameroon were asked about informal seed trade of potato, sweetpotato, cassava, and
328 banana between regions. In the expert knowledge elicitation, informal seed trade was defined as 'seed
329 obtained from neighbors, local markets, or uncertified seed producers or traders'. For each potential link
330 between a pair of regions, the link weight assigned was the proportion of experts who reported that there
331 was informal trade between that pair. This proportion was used as a measure of confidence for the
332 potential existence of trade between two regions or states. Higher awareness of trade among experts may
333 be associated with higher trade volume. The node strength, or the sum of link weights, of informal seed
334 trade was then calculated for each region using the igraph R package (version 1.5.0) (Csárdi et al., 2023).
335 These estimates of informal trade were compiled for each crop in Cameroon and represented as networks
336 using the ggraph R package (version 2.1.0), a package for analyzing and visualizing networks (Pedersen,
337 2022). The informal seed trade networks between regions were then plotted on a map of Cameroon with
338 political administrative boundaries, using the rgeoboundaries R package (version 1.2.9000) (Dicko, 2023).

339 2.4 Trade with neighboring countries: Informal seed trade and food commodity trade

340 Experts were asked about informal trade of potato, sweetpotato, cassava and banana seed with
341 neighboring countries. Experts indicated which countries they thought informally imported seed from and
342 exported seeds to Cameroon or Ethiopia for each crop, where "informal seed" was defined as seed
343 "obtained from personal seed (seed saved from prior harvests/stocks), neighbors, local markets, or
344 uncertified seed producers." We created an informal trade network based on the total number of experts
345 who reported trade occurred between two countries. We rescaled these reports to represent the
346 proportion of experts who identified potential informal trade routes, for example, if 7 of a total of 10
347 experts identified trade between Cameroon and the Central African Republic, the link weight would be
348 0.7. We created these informal import and export networks for potato, sweetpotato, cassava, and banana
349 for Cameroon, and potato and sweetpotato for Ethiopia, and represented them as networks using the
350 ggraph R package (version 2.1.0) (Pedersen, 2022).

351 Trade in food commodities generally represents a lower risk for the spread of pathogens and
352 pests compared to trade in planting materials, but can also be a factor if effective phytosanitary measures
353 are not in place. For crops like potato trade in food commodities is a higher risk, because tubers that are
354 imported as food may later be used as seed; planting of food commodities is more unusual for
355 sweetpotato, and not a risk for cassava and banana. For the analysis of food commodity trade, FAO import
356 and export data were analyzed for Cameroon, Ethiopia, and their respective neighboring countries
357 (FAOSTAT, 2021). Here, the FAO data represents the trade of food, or "trade that occurs within a legal
358 framework and is obtained from certified governmental distributors." Products manufactured by roasting
359 or sterilization were excluded in this trade data, because of their reduced risk. FAO trade data were
360 assembled for each crop, where the trade volume (in tons) between each pair of countries was averaged
361 for 2006-2020 (FAOSTAT, 2021). The trade volumes were then rescaled to represent the proportion of
362 crop-specific trade for a country. For example, if Ethiopia exported on average 300 kg of potato to

Djibouti, where the most exported was 1000 kg, the link weight would be 0.3. The FAO food trade data were assembled in a network and compared with the informal seed trade as reported by experts.

3 Results

3.1 Cropland connectivity

Crop landscape connectivity was used to identify locations likely to play important roles in the spread of pests and pathogens based on host availability and dispersal models. We evaluated cropland connectivity separately for potato and sweetpotato in Cameroon and Ethiopia, and also for banana and cassava in Cameroon.

In Cameroon, the analysis of crop landscape connectivity indicated that, for banana pathogens and pests, locations in the Southwest, West, Northwest, Centre, South, East, and Adamawa regions have high banana cropland connectivity, based on host availability **(Figure 2)**. For cassava, many regions of Cameroon, except in the Southwest region, have locations with high cassava cropland connectivity within country and to highly connected large cassava croplands in neighboring countries like Nigeria and Chad **(Figure 2).** For potato, locations in the West, Northwest, and Adamawa regions have higher cropland connectivity **(Figure 2**). These higher-risk potato cropping areas are fairly small, reflecting the limited extent of potato production across Cameroon and the geographic isolation from more extensive potato production in neighboring countries. For sweetpotato, locations in the West, Northwest, Adamawa, North and Far-Noth regions have high connectivity **(Figure 2),** based on host availability, with locations in the Northwest and West having the highest cropland connectivity across these regions.

For Ethiopian potato production, locations in a large expanse across central Ethiopia have higher cropland connectivity, spanning across Amhara, Oromia, Sidama and into the former Southern Nations,

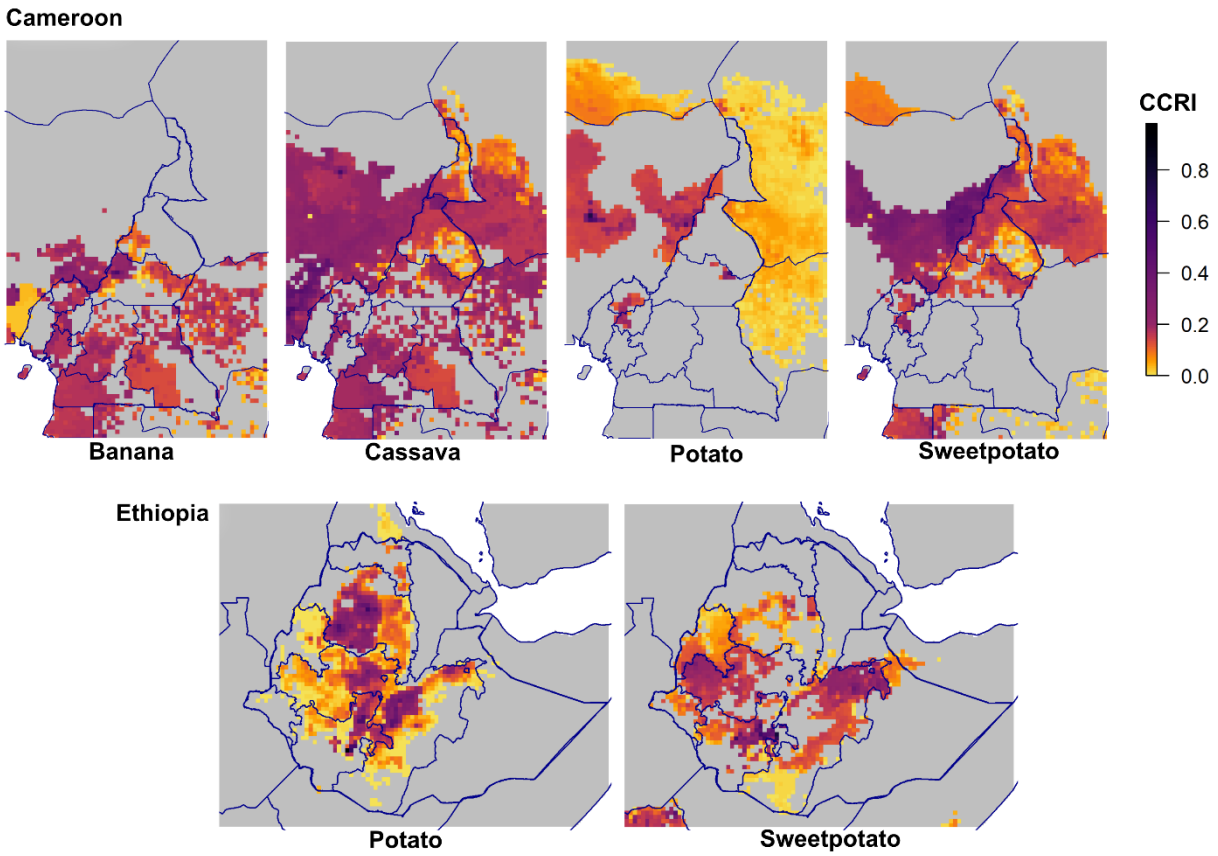

Figure 2. Maps of a cropland connectivity risk index for banana, cassava, potato, and sweetpotato in Cameroon and for potato and sweetpotato in Ethiopia. Locations with more crop production are generally more important for the buildup and spread of crop-specific pathogens and pests, all else being equal. Cropland connectivity analyses build on this idea and also take into account whether a location is isolated or might act as a bridge between other production areas. The cropland connectivity risk index is based on networks of potential spread of a crop-specific pathogen or pest across a landscape of crop production; locations with higher cropland connectivity are likely to be more important for pathogen and pest establishment and spread, based on host availability.

Nationalities and Peoples Region (SNNPR), with the highest CCRI scores occurring in the SNNPR and central Amhara regions **(Figure 2)**. For Ethiopian sweetpotato, key locations include parts of western Oromia and Benishangul-Gumuz, the border between the former SNNPR and Sidama, and eastern Oromia including Harari and Dire Dawa **(Figure 2)**. The highest CCRI scores for Ethiopian sweetpotato were on the border between Sidama and the former SNNPR. Neighboring countries were not strongly connected to

389 Ethiopia in potato and sweetpotato cropland networks, as the reported harvested cropland production in
390 neighboring countries was relatively low **(Figure 2) (IFPRI, 2020)**.
391

392 **3.2 Expert knowledge elicitation: Pathogen and pest communities**

393 Experts noted locations where they knew pathogens and pests were present. Here, absence of
394 evidence is not evidence of absence, but locations noted by experts are generally more well-known to
395 have important problems with pathogens and pests. For banana in Cameroon, experts had the most
396 experience in the Centre region, followed by the South, Littoral, and then the East and Northwest regions.
397 The most pathogens and pests, eight, were noted by experts in the South zone**.** Anthracnose (caused by
398 *Colletotrichum musae*) was noted present in most regions of Cameroon, and nematodes and yellow
399 sigatoka were noted present in many regions. Banana seed degeneration in Cameroon was noted by
400 experts to be associated with many pathogens/diseases and pests, including nematodes, BBTV, banana
401 weevil, anthracnose, and rhizome soft rot (caused by *Pectobacterium*). In post hoc discussions, experts
402 also mentioned the importance of black Sigatoka disease.

403 For cassava in Cameroon, the East, Centre, and South regions were noted to have the presence of
404 all 13 pathogens that were included in the expert knowledge elicitation survey**.** Cassava green mite,
405 cassava root rot, cassava mosaic disease, cassava mealybugs and cassava whitefly were noted as present
406 in every region across Cameroon. Cassava seed degeneration was noted to be associated with many pests
407 and diseases, including CMV, cassava root rot (caused by *Fusarium* spp.), cassava anthracnose disease,
408 ACMV, *Colletotrichum* spp., and cassava whitefly.

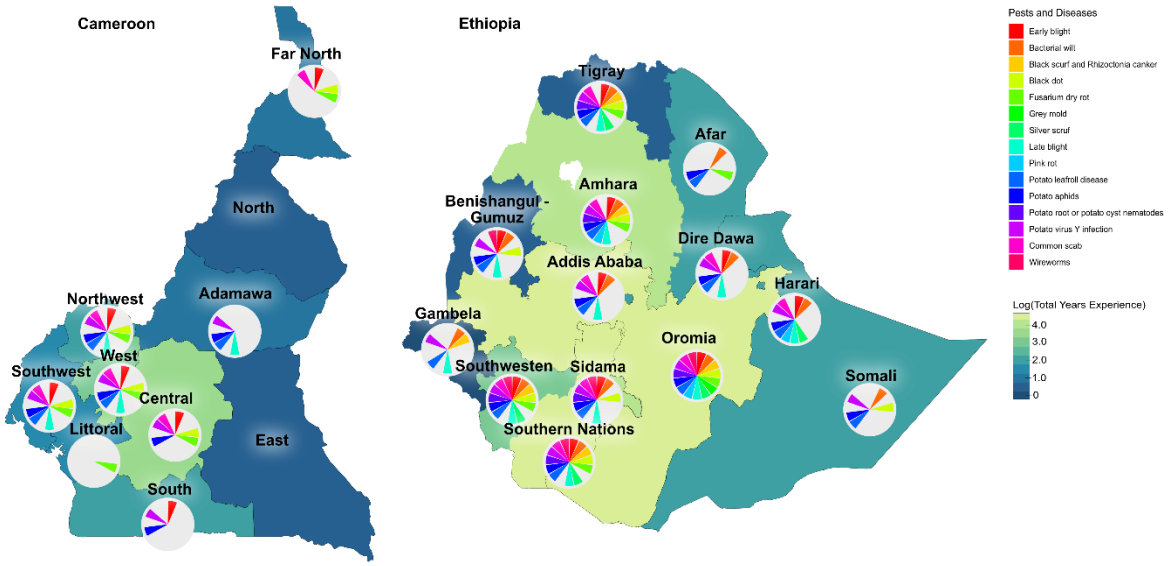

Figure 3. The major potato pests and pathogens noted in expert knowledge elicitation for Cameroon and Ethiopia (based on Ethiopian states as of March 2023). The color in a region or state is proportional to the log-transformed sum of the years of experience reported by the experts for potato in that region or state, and can be interpreted as a measure of confidence in reports by experts for a region or state. The circular bar charts show the pests and diseases reported as present by at least one expert in each region or state.

For potato in Cameroon, the western border was noted by experts to have most major pathogens and pests evaluated, with the Northwest and Southwest regions noted as having at least eight of those evaluated **(Figure 3)**. Early blight (caused by *Alternaria solani*), PVY, potato aphids and Fusarium dry rot were noted to be present in seven of the ten regions across Cameroon. Potato seed degeneration was noted to be associated with late blight (caused by *Phytophthora infestans*), PVY, PLRV, bacterial wilt, Fusarium dry rot, and nematodes.

For sweetpotato in Cameroon, the West region was noted to have most major pathogens and pests, with the South region having six pathogens noted. For the Northwest, West, Centre, and Littoral regions, at least five were noted. Early blight (caused by *A. solani*) and bacterial wilt (caused by *Ralstonia solanacearum*) were noted as present in most regions of Cameroon. Sweetpotato seed degeneration was reported to be associated with sweetpotato viruses, Alternaria blight, and Fusarium root rot. In post hoc discussions, experts noted the importance of weevils.

422 For Ethiopian potato, central zones were noted in expert knowledge elicitation to have most
423 major pests and pathogens, with Oromia noted as having at least twelve of the pathogens and pests
424 **(Figure 3).** The former SNNPR, Southwestern, Amhara and Tigray regions each had reported pathogen
425 communities of at least ten pathogens. Experts noted that PLRV was present in every region across
426 Ethiopia. PVY and potato aphids were noted as present in most regions. Experts selected the key causes of
427 potato seed degeneration in Ethiopia to be *Phytophthora infestans*, PVY, PLRV, potato aphids, early blight,
428 and bacterial wilt.

429 For Ethiopian sweetpotato, southern zones were noted by experts to have the highest pest and
430 pathogen communities, with Sidama and the former SNNPR both noted as having at least 8 pathogens.
431 Alternaria blight and the sweetpotato weevil were noted as present in most regions across Ethiopia.
432 Experts selected the key causes of seed degeneration as sweetpotato viruses, sweetpotato weevil,
433 *Alternaria bataticola*, and sweetpotato aphids.

434 **3.3 Expert knowledge elicitation: Within-country informal seed trade in Cameroon**

435 We analyzed the network of seed transfers between regions in Cameroon as noted by experts for
436 potato and sweetpotato, to assess the risk of pathogen and pest spread through seed between regions.
437 For informal potato and sweetpotato seed trade in Cameroon, all the regions were reported to be
438 interconnected. There was high node strength for seed trade reported in the West region for potato (77%
439 of experts noting trade) and in the Centre and Littoral regions for sweetpotato (43% of experts noting
440 trade) **(Figure 4).**

441 For banana and cassava in Cameroon, regions were reported to be connected. Experts noted high
442 regional informal seed trade strength for banana in the Southwest, Littoral, East, West and South regions
443 for cassava in the South, Centre, Littoral, West and East regions **(Figure 4).** The experts also reported that,
444 due to the current crisis in the Northwest and Southwest regions of Cameroon and the conflict with Boko

Haram in the Far-North region, growers have moved to other regions and neighboring countries with their goods, including food and/or seed. Experts also highlighted the vulnerable situation of many of these growers working in neighboring regions and countries.

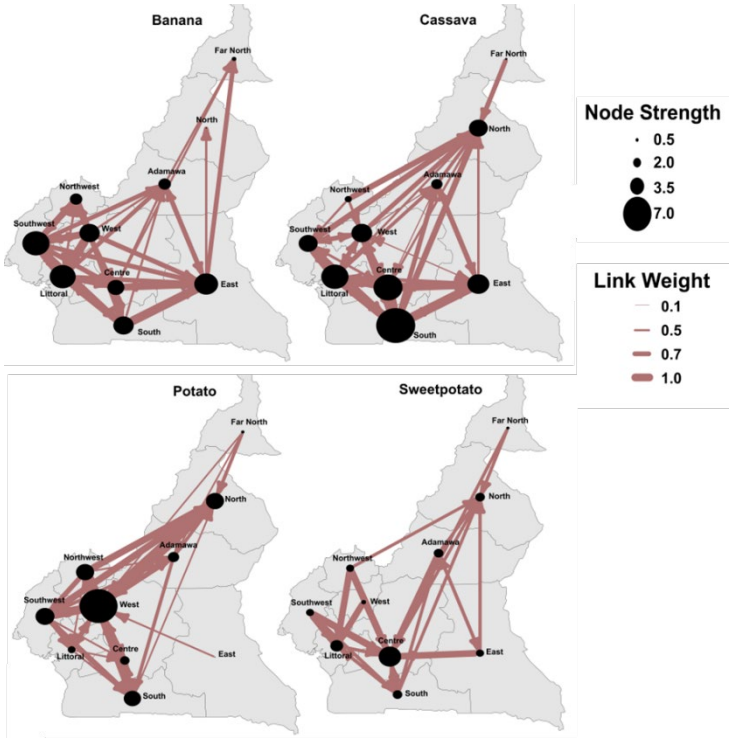

Figure 4. Informal seed trade networks between regions in Cameroon as noted in expert knowledge elicitation. Node size is proportional to node strength, the sum of link weights. Link weights are the proportion of experts who reported the occurrence of informal trade between the linked regions. This study evaluated only whether movement of planting material between locations occurred. Future studies could benefit from evaluating the frequency and quantity of seed movement within these countries, an important factor for epidemic and invasion risk that is a current information gap. In post hoc discussions, some experts thought that information about seed flow and trade networks was not common among experts, so the uncertainty of these estimates may be higher. Movement of high quantities of perishable seed such as sweetpotato vines is likely to be uncommon at large distances.

450 3.4 Informal seed trade with neighboring countries

451 We used expert knowledge elicitation to characterize informal seed trade networks that link
452 Cameroon and Ethiopia with their neighboring countries. These networks were evaluated for potato and
453 sweetpotato for both Cameroon and Ethiopia, and also for banana and cassava for Cameroon.

454 For informal 80 of banana seed in Cameroon, 40% of experts (4) noted exports to Gabon, and
455 30% (3) noted imports from Gabon and exports to Nigeria **(Figure 5, I)**. Cameroon was noted to receive
456 imports from Nigeria, the Central African Republic, Gabon, and the Republic of Congo, and noted to
457 informally export to Chad, Nigeria, Central African Republic, Equatorial Guinea, Gabon, and the Republic
458 of Congo.

459 For informal cassava seed trade in Cameroon, 72% of experts (13) noted exports to Gabon, and
460 50% (9) noted imports from Nigeria **(Figure 5, I)**. Informal imports and exports were noted by experts for
461 all neighboring countries, with the exception of informal imports from Chad **(Figure 5, I)**.

462 For informal potato seed trade in Cameroon, 38% of experts (5) noted informal imports from
463 Nigeria to Cameroon, and 30% (4) noted informal export from Cameroon to Gabon **(Figure 5, I)**. Informal
464 exports and imports of potato seed between all neighboring countries and Cameroon was noted by at
465 least one expert, with the exception of imports from the Republic of Congo.

466 For informal sweetpotato seed imports, 29% of experts (2) noted that Gabon, Nigeria, and the
467 Central African Republic imported from Cameroon, and 29% of experts (2) noted that Cameroon exported
468 to Gabon and the Central African Republic **(Figure 5, I)**. Cameroon was noted to informally export to
469 Nigeria and Republic of Congo by 14% (1) of experts. No informal imports were noted from Chad,
470 Equatorial Guinea, or the Republic of Congo, and no informal exports were noted to occur to Equatorial
471 Guinea or Chad.

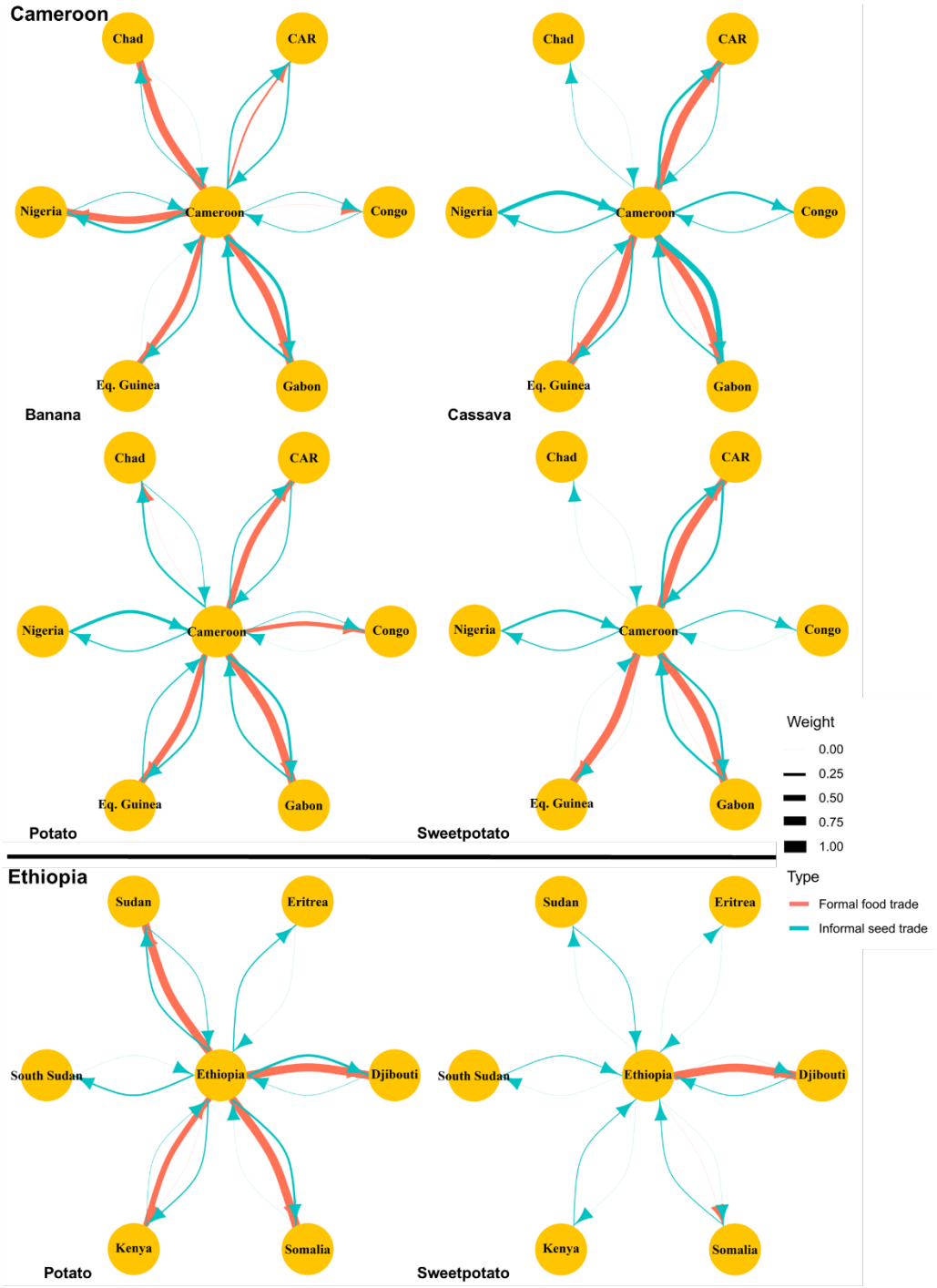

Figure 5. Informal seed trade networks (blue links) noted in expert knowledge elicitation, and food commodity trade networks (red links; FAO trade databases for 2006-2020), with neighboring countries for Cameroon and Ethiopia. Link width for informal seed trade is proportional to the relative confidence in the occurrence of trade (based on the proportion of experts reporting it). Link width for food trade is proportional to the volume of trade (FAO). Note that food commodity trade may be particularly important as a risk factor for pathogen or pest spread for crops like potato, since ware potato can be used as seed. CAR refers to the Central African Republic, Congo to the Republic of Congo, and Eq. Guinea to Equatorial Guinea.

For the informal Ethiopian potato seed trade, 30% of experts (6) noted export to Djibouti, and

473 25% (5) noted exports to Somalia and Sudan **(Figure 5, II)**. No experts noted informal imports from
474 Somalia, Eritrea, and South Sudan. Informal exports were noted for all neighboring countries. Informal
475 trade of sweetpotato seed was reportedly rare from Ethiopia, where no informal exports of sweetpotato
476 seed were noted **(Figure 5, II)**. Informal imports were noted from all neighboring countries except Eritrea,
477 with only 11% of experts (1) noting these imports.

478 **3.5 Food commodity trade with neighboring countries**

479 Food commodity trade is lower risk than informal seed trade, particularly for crops like banana
480 and cassava where the food commodity cannot be used as planting material, but it still requires attention
481 to ensure phytosanitary procedures. We used FAO trade data to characterize food commodity trade
482 networks that link Cameroon and Ethiopia with their neighboring countries.

483 The highest volume trade for Cameroon in banana fruit was exports to Gabon, and secondly to
484 Chad. Cameroon exported to Gabon, Chad, Nigeria, Equatorial Guinea, and the Central African Republic
485 **(Figure 5, I)**. For trade of cassava tubers in Cameroon, FAO reported the highest trade volume occurring as
486 exports to Gabon. Exports were also to Equatorial Guinea and the Central African Republic **(Figure 5, I)**.
487 For Cameroonian trade in ware potato, only exports were reported with the Republic of Congo, the
488 Central African Republic, Equatorial Guinea, and Gabon, with the highest trade volume average as exports
489 to Gabon. For the trade in sweetpotato roots for consumption, bidirectional trade occurred between
490 Cameroon and Gabon, with the highest trade volume occurred from Cameroon exports to Gabon.
491 Cameroon also export to the Central African Republic and Equatorial Guinea. No trade was reported to
492 occur with Chad and the Republic of Congo **(Figure 5, I)**. However, in post hoc discussions, an expert in
493 Cameroon reported observing large volumes of roots shipped from Cameroon to Chad daily, an illustration
494 of how expert knowledge can supplement FAO reports.

For Ethiopian trade in ware potato, the highest trade volume was Ethiopian exports to Somalia, and then imports from Kenya. No imports or exports were reported between South Sudan and Eritrea, and no imports from Sudan, Djibouti, or Somalia **(Figure 5, II)**. Sweetpotato tuber imports and exports were also reportedly rare, with Ethiopia exporting to Djibouti and Somalia **(Figure 5, II).**

4 Discussion

4.1 Components of this baseline national plant health risk analysis

These analyses provide a baseline version of a national plant health risk analysis for potato and sweetpotato in Cameroon and Ethiopia, and for banana and cassava in Cameroon. Candidate priority locations, for surveillance and mitigation to reduce pathogen and pest risk, were identified based on cropland connectivity (**Figure 2**), informal seed trade (**Figures 4 and 5**), and commodity trade (**Figure 5**). Expert knowledge elicitation also provided a geographic summary of major RTB pathogens and pests noted as present in the countries (**Figure 3**). This national plant health risk analysis is intended to inform humanitarian and development actions, and to be improved over time as greater coordination is achieved between plant pathology research outputs and decision-making by humanitarian and development organizations.

The spread of crop pathogens and pests is driven by a complex interplay of factors including environmental conduciveness to pathogen and pest reproduction, natural and human-driven disasters , the formal and informal movement of planting material and harvested products, as well as the density and connectivity of crops (Andersen Onofre et al., 2021; Buddenhagen et al., 2022; Garrett et al., 2022; Margosian et al., 2009; Nduwimana et al., 2022; Xing et al., 2020). Many actors may inadvertently contribute to pathogen and pest movement: growers sharing seed, traders selling local seed, general crop traders, and humanitarian groups and governments providing emergency or developmental assistance. Cropland connectivity analyses (**Figure 2**) identify locations likely to be important for the establishment

518 and spread of crop-specific pathogens and pests, based on crop host availability (Margosian et al., 2009;
519 Xing et al., 2020). All else being equal, locations with more crop production are generally more important
520 in epidemics or invasions, for the buildup and spread of pathogens and pests through local trade, spore
521 dispersal, insect flight, etc. Cropland connectivity analysis adds to that idea by accounting for the
522 geographic distribution of production, such that isolated production is less important in epidemics while
523 'bridges' between production areas are likely to be more important. (Buddenhagen et al., 2022). More
524 direct information about trade fills in other dimensions of the potential for pathogen and pest movement
525 (**Figures 4 and 5**).

526 The current distribution of pathogens and pests is key for identifying farmers' most important
527 problems and for understanding the potential spread of pathogens and pests to locations where they are
528 currently absent or rare (**Figure 3**). Expert knowledge elicitation has been used in other systems to
529 evaluate phytosanitary risk, for example by Andersen Onofre et al. (2021) to identify phytosanitary
530 strategies for protecting potato seed systems in the Republic of Georgia. In a study linked to the one
531 reported here, Etherton et al. (2025) created risk maps for potato seed systems in Ethiopia and evaluated
532 regions at a high risk for pests and diseases, particularly *Ralstonia solanacearum*. Expert knowledge
533 elicitation was also used to evaluate the informal trade network for seeds, and the risk of pathogen and
534 pest spread between regions.

535 **4.2 Ongoing improvement of a national plant health risk analysis**

536 When resources are available, there are many possibilities for improving on this baseline national
537 plant health risk analysis (**Figure 6**). For example, the cropland connectivity analyses represent a simplified
538 view of the risk of spread by averaging across potential dispersal parameters, to represent many potential
539 pathogens and pests. When dispersal is well-characterized for a particular pathogen or pest species, the
540 cropland connectivity analysis can be implemented specifically for that species, at the resolution needed,

541 and potentially expanded to a fuller habitat connectivity analysis using the geohabnet package (Keshav et
542 al., 2024), including other geographic traits such as environmental conduciveness to the species. The
543 cropland connectivity analysis may also be improved as crop density maps improve in quality (IFPRI, 2024;
544 Tang et al., 2024). Cropland connectivity analyses can also be a first step for scenario analyses for
545 evaluating regional pest and disease management strategies, by providing an estimate of the potential
546 epidemic or invasion network for simulation experiments in scenario analyses (Etherton et al., 2023;
547 Garrett, 2021; Wiebe et al., 2018).

548 Expert knowledge elicitation can provide a baseline summary of expert perceptions, for ongoing
549 improvement as new information becomes available. Experts have gaps in their knowledge, leading to
550 incomplete or biased information. Experts may tend to have less knowledge about locations where a
551 particular crop is less commonly produced, so that there is less 'experiential sampling effort' in those
552 locations, in terms of expert knowledge. When resources are available for monitoring of pathogens and
553 pests or trade, new information can supplement summaries of expert knowledge. Expert opinion,
554 although potentially biased, is still useful, and can serve as the basis for further statistical inference, such
555 as in a Bayesian statistical analysis which use expert knowledge about a parameter (for example, pest
556 abundance) in the prior distribution (Ford et al., 1998; O'Hagan, 2019). In this study, we incorporate link
557 weights indicating the relative confidence level across experts. After experts consider responses
558 individually, discussion in small groups, as in methods like the Sheffield protocol for expert knowledge
559 elicitation, can help refine expert opinions (Gosling, 2018; O'Hagan, 2019).

560 Two points for improvement to the formulation of questions for experts became apparent in this
561 study. First, greater detail about the prevalence of pathogens and pests would be useful, in addition to
562 presence/absence data, along with consideration of what experts anticipate could be emerging pathogens
563 and pests in the near future. Second, the baseline information reported here addresses whether seed
564 movement between locations occurs. Future evaluations could build on this by clarifying how frequent

565 long-distance movement of perishable vegetative planting material is. The level of long-distance trade
566 within a country is an important question from an epidemiological standpoint: long-distance pathogen
567 movement can play a particularly important role in pathogen invasions across diverse regions. In post hoc
568 discussions, some experts thought that information about seed flow and trade networks was not common
569 among crop and seed experts, so that there may be higher uncertainty associated with seed trade
570 networks estimated using expert knowledge elicitation. Targeted follow-up studies addressing the quantity
571 of seed moved through networks would be needed to decrease uncertainty.

572 A national plant health risk analysis could also benefit from additional information and from links
573 to larger and more general studies (Plex Sulá et al., 2024). For example, yield loss is an important
574 component of risk, but detailed yield loss estimates are expensive. Savary et al. (2019) used an expert
575 survey to estimate global yield losses due to pathogens and pests for five major food security crops,
576 including potato. Information about the geographic distribution of current yield loss to pathogens and
577 pest, and of management strategies adopted, is another potentially valuable component; these are also
578 candidates for expert knowledge elicitation because experts with field experience often have useful
579 knowledge but direct field surveys across large geographic areas are expensive to implement. Expert
580 knowledge elicitation and habitat connectivity analysis are part of the developing R2M toolbox for rapid
581 risk assessment to support mitigation of plant pathogens and pests (garrettlab.com/r2m), designed for
582 continual improvement based on lessons learned in applications across countries and crop systems.
583 Related tools focusing on seed systems include the seed emergency response tool (Sperling et al., 2022),
584 the multi-stakeholder framework for RTB seed systems (Bentley et al., 2018), and other components of

585 the CGIAR tools4seedsystems toolbox (Andrade-Piedra et al., 2023). These tools can be used in
586 conjunction and incorporated into comprehensive risk management frameworks. National or regional
587 analyses can ultimately be integrated in projects such as the Global Plant Health Assessment (Acuña et al.,
588 2023), the proposed Global Surveillance System for Plant Disease (Carvajal-Yepes et al., 2019; Prasanna et
589 al., 2022), and databases such as the CABI digital library (https://www.cabidigitallibrary.org/) .
590 Improvements can continually be made, in terms of the overall quality of data and modeling, and also in
591 terms of the quality of translation for use in humanitarian applications.

592 **4.3 Translating a national plant health risk analysis to support humanitarian activities**

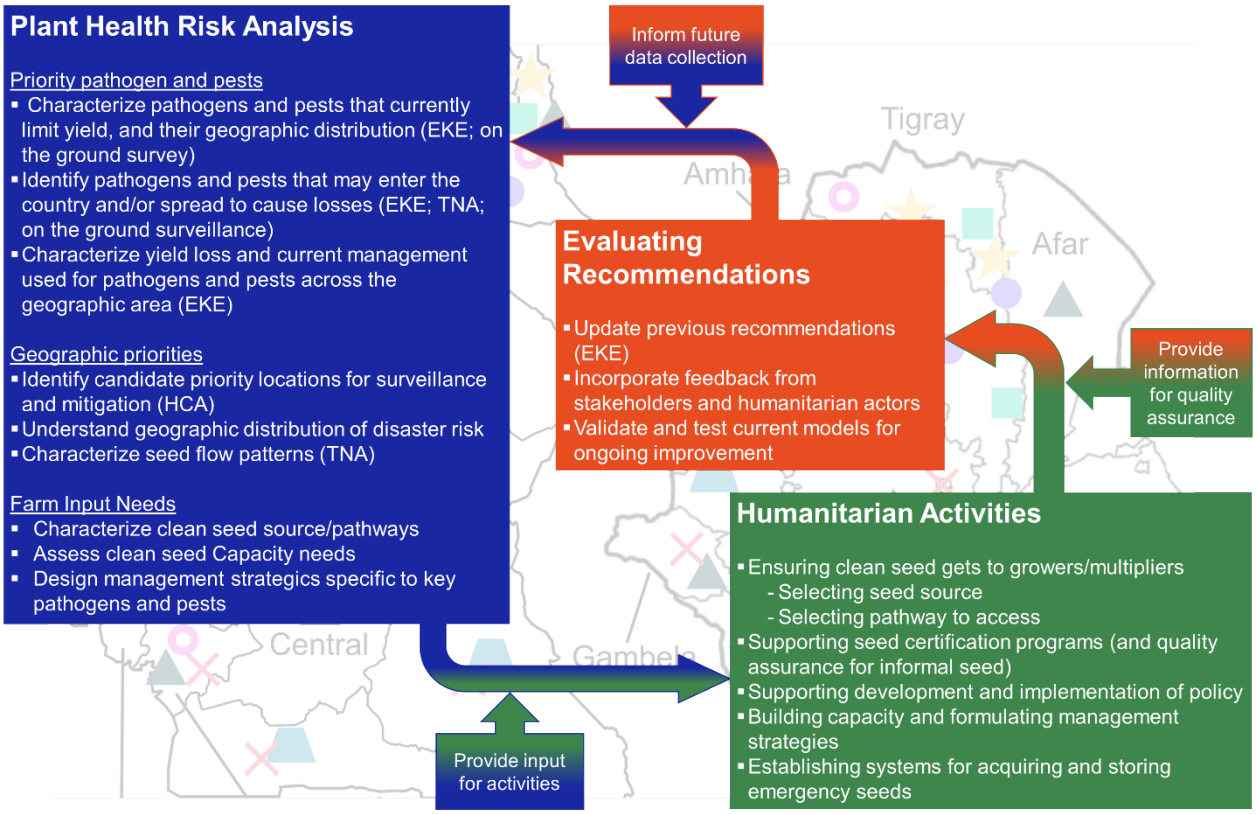

Figure 6. A framework for development and ongoing improvement of a national plant health risk analysis, to assist in addressing crop health in humanitarian settings. This approach can help to safeguard food production for vulnerable communities prior to and following disasters, and help to streamline and optimize humanitarian assistance. EKE: expert knowledge elicitation, HCA: habitat connectivity analysis (including cropland connectivity analysis, and TNA: trade network analysis.

593 During times of crisis, first-order humanitarian aid should clearly be allocated to providing
594 affected people with basic needs such as food, water, and shelter. A priority shortly after is to spur
595 agricultural production for growers' own food production, and sales, and overall resilience. For RTB crops,
596 attention should focus on supporting growers in obtaining quality seed, including growers displaced from
597 neighboring regions or countries (Etherton et al. 2024). Seed should have low pathogen and pest levels,
598 and none that would be new introductions to a location, to break or at least reduce cycles of seed
599 degeneration (Navarrete et al., 2022; Thomas-Sharma et al., 2017). For example, if humanitarian agencies
600 purchase ware potato to distribute as seed, this increases the risk of pests and disease for the people they
601 are trying to benefit. Clean or certified seed is a costly investment, and currently, the capacity to distribute
602 clean seed across the country is not in place in Cameroon and Ethiopia. Humanitarian practitioners should
603 use caution in sourcing seed, drawing on information about the current distribution of pathogens and
604 pests to reduce the chances of introducing pathogens and pests (**Figure 6**). Risk assessment of potential
605 seed sources, initial seed testing (when stocks are obtained), maintenance of seed quality at multiple
606 stages of the delivery chain, and charting of specific sources of original clean planting materials are all
607 essential steps for humanitarian programs before and during on-the-ground interventions.

608 This baseline analysis is a first step toward creating a national plant health risk analysis to identify
609 geographic priorities for aid, to optimize deployment of quality seed that is currently available, in the
610 context of disaster plant pathology (Etherton et al., 2024) or for agricultural development more generally.
611 For example, providing clean seed to growers in locations with common seedborne pathogens and pests
612 may be a candidate priority (Buddenhagen et al., 2022). Cropland connectivity analysis, or more general
613 habitat connectivity analysis, could be used before, during, and after crises to identify candidate priority
614 locations where preventative or mitigation efforts are likely to have a greater impact on slowing pathogen
615 or pest spread (Andersen Onofre et al., 2021; Thomas-Sharma et al., 2017)(Xing et al., 2020). Maps of
616 connectivity (CCRI) show surrounding regions that may also play an important role in epidemics, which

617 may be priorities for providing clean seed to fleeing and displaced populations who are planting in new
618 locations, or for seed testing to mitigate disease establishment. Locations that have informal trade with
619 many other regions are also a candidate priority, to reduce dispersal of pathogens and pests. Following a
620 crisis, understanding the informal movement of seed (**Figures 4 and 5**), as well as trade in food, can help
621 identify management intervention priorities along informal trade chains, including growers, traders, and
622 seed producers (Andersen Onofre et al., 2019; Delaquis et al., 2018; Nduwimana et al., 2022).

623 Capacity building can draw on information about important pathogens and pests in a priority
624 region, and their potential movement. Training in the humanitarian practice community can address best
625 practices for detecting and managing pathogens and pests, so that practitioners are prepared to evaluate
626 seed quality and to provide training to farmers, in turn. Training could draw on the information in a
627 national plant health risk analysis, and practitioners could provide feedback to improve the analysis and its
628 utility to humanitarian personnel (**Figure 6**). If humanitarian practitioners can provide displaced farming
629 families with basic information about identification of important pathogens and pests and their
630 management, this can reduce the risk of spread to other production and help to maintain yield.

631 Seed degeneration is likely exacerbated in Cameroon and Ethiopia since significant numbers of
632 refugees and displaced people have been integrated into local communities, adding a further challenge to
633 accessing clean seed and food. There is often a lack of networks for accessing formal services and
634 resources (ECPHAO, 2023; TGHAT, 2022). In Cameroon, for example, 90% of the agricultural market, in
635 general, is informal (OCHA, 2023a). Experts pointed out that, with multiple conflicts and crises and
636 repeated natural disasters (such as droughts, floods, or landslides), both in Cameroon and neighboring
637 countries (Nigeria and the Central African Republic), populations tend to move to neighboring countries or
638 villages, return to their villages during periods of calm or harvests, and flee again as soon as conflict
639 intensity increases. ECPHAO (2023) reports that the ongoing separatist conflict in the Northwest and
640 Southwest regions has displaced 80,000 Cameroonians to neighboring villages in Nigeria, while violence in

641 the Central African Republic and conflict with Boko Haram in northern Nigeria led to a massive influx of
642 over 491,000 refugees into neighboring Cameroonian villages (ECPHAO, 2023). Inter-community conflicts,
643 linked to the scarcity of water and other resources, broke out in 2021 between populations in the Far
644 North, resulting in the displacement of over 70,000 people, 35,000 of whom sought refuge in Chad
645 (ECPHAO, 2023; FAO, 2021b). Growers fleeing with their goods (including fresh planting material) have the
646 potential to introduce seedborne pathogens and pests into new regions, which is particularly important if
647 they are new pathogen or pest species or key subpopulations (such as new pathogen mating types).
648 Introductions may also be particularly important in regions that have high cropland connectivity, such as
649 some locations in Chad. The Boko Haram conflict in northeast Nigeria caused 138,000 refugees to flee to
650 Far North Cameroon (ECPHAO, 2023). Foyou et al. (2018) also reported that in Cameroon, the crisis
651 caused by Boko Haram in the Far North region increased the vulnerability of the agricultural and economic
652 system and caused the internal and external displacement of millions of people.

653 In Ethiopia, flooding in central Amhara (**Figure 1**) can occur along with conflicts such as the Tigray
654 Civil conflict affecting the Amhara-Tigray border. With ongoing improvement to the maps of the pest and
655 pathogen communities present in Amhara (**Figure 3**), when a flooding disaster strikes, humanitarian aid
656 could prioritize management of diseases like potato early blight, bacterial wilt, and late blight, which are
657 exacerbated during floods (Guchi, 2015; Meno et al., 2020). When growers flee from disasters like the
658 Tigray Civil conflict, they may take seed with them, unknowingly bringing these pest and pathogen
659 communities with them. When locations are understood to be particularly important in terms of epidemic
660 connectivity, as suggested in the baseline analysis for Oromia (**Figure 2**), prioritizing resources like clean or
661 good quality seed for displaced people fleeing to such regions is a good strategy. For example, Etherton et
662 al. (2025) concluded that the risk of reintroducing the *Ralstonia solanacearum* species complex (RSSC) to
663 Ethiopia from Kenya through trade was an important consideration, as was the risk of spreading the RSSC
664 from Ethiopia to neighboring countries. In Ethiopia, IOM (2023) reported that ethnic and/or territorial

665 conflicts and drought had a huge impact on agricultural production, causing the internal displacement of
666 over 4.8 million people in 2022 and 2023. An assessment of agricultural performance conducted in 2022
667 reported that about 1.2 million households in four regional states of Ethiopia needed emergency seed and
668 other input support to resume agricultural activity in the 2023 cropping seasons (RBA, 2022).

669 Knowledgeable farmers have some options for protecting their crop health even when seed
670 systems lack formal seed testing. Farm-to-farm transfer of planting material usually occurs at the village
671 level, where recipient farmers could have first-hand knowledge of the health of their neighbors' planting
672 material (Sperling & Almekinders, 2023; Sperling & McGuire, 2010). In some cases, farmers may even
673 inspect the fields themselves before accepting seed. Planting material transactions also routinely take
674 place in local and regional markets – for potato and increasingly for other RTB crops. Seed is sometimes
675 purchased from traders who may source from geographically distant or agro-ecologically diverse farms
676 (Sperling et al., 2020). As a result, farmers typically rely on information provided by intermediaries, like
677 neighboring farmers, local market traders, and itinerant traders selling across expansive regions. Some of
678 these sellers do have their own criteria for screening seed quality, like visual cleanliness of the planting
679 material or its vigor, or its freshness of color. However, for many, screening for disease, especially diseases
680 with more cryptic symptoms, is a formidable challenge. Farmers, traders, and humanitarian aid groups
681 should be trained in selection for good-quality seed, combined with a strategy of regular seed
682 replacement, which could prove beneficial in areas with no formal seed system. This should be the first
683 line of defense for safeguarding seed systems: education and training.

684 ## 4.4 Conclusions

685 Integrating the best available national plant health risk analysis in routine disaster risk reduction
686 activities in countries experiencing multiple disasters can provide a baseline for rapid synthesis and
687 verification during a crisis, directing practical humanitarian and government action. At a farm scale, the

best available national plant health risk analysis can be used by extension specialists to design specific education and testing protocols in response to a disaster. At a larger scale, a national plant health risk analysis can be used by government agencies and humanitarian groups to allocate clean seed and management efforts both prior to and in response to disasters. A national plant health risk analysis could also support long-term development efforts in peaceful periods, including targeted breeding for disease and pest resistance. This proactive approach could help vulnerable regions or countries to be better prepared for disasters and to recover from them more quickly. Aid, whether governmental or humanitarian, is a crucial part of agricultural sustainability and should focus on the development of sustainable long-term strategies, involving governmental agencies to develop more formal seed testing programs nationally. It is through the collaboration of humanitarian groups, governmental programs, national agricultural research institutions, traders, and farmers, themselves, that sustainable agriculture can be achieved in the face of humanitarian disasters.

Statements and Declarations

The authors declare that they have no conflict of interest.

Sources

Acuña, I., Andrade-Piedra, J., Andrivon, D., Armengol, J., Elizabeth Arnold, A., Avelino, J., Bandyopadhyay, R., Bihon Legesse, W., Bock, C. H., et al. (2023). A global assessment of the state of plant health. *Plant Disease*, *107*(12), 3649-3665.

Alasow, A. A., Hamed, M. M., & Shahid, S. (2023). Spatiotemporal variability of drought and affected croplands in the horn of Africa. *Stochastic Environmental Research and Risk Assessment*, 1-16. https://doi.org/10.1007/s00477-023-02575-1

Andersen Onofre, K. F., Buddenhagen, C. E., Rachkara, P., Gibson, R., Kalule, S., Phillips, D., & Garrett, K. A. (2019). Modeling epidemics in seed systems and landscapes to guide management strategies: The case of sweet potato in northern Uganda. *Phytopathology*, *109*(9), 1519-1532. https://doi.org/10.1094/PHYTO-03-18-0072-R

Andersen Onofre, K. F., Forbes, G. A., Andrade-Piedra, J. L., Buddenhagen, C. E., Fulton, J. C., Gatto, M., Khidesheli, Z., Mdivani, R., Xing, Y., & Garrett, K. A. (2021). An integrated seed health strategy and phytosanitary risk assessment: Potato in the Republic of Georgia. *Agricultural Systems*, *191*, 103144. https://doi.org/10.1016/j.agsy.2021.103144

Andrade-Piedra, J., Dontsop, P., Dunia, D., Kulakow, P., Harahagazwe, D., Mouafo-Tchinda, R., Omondi, A., Ogero, K., Rajendran, S., & McEwan, M. (2023). Tools4SeedSystems: Working towards resilience through root, tuber and banana crops in humanitarian settings. Capacity needs assessment for root, tuber and banana seed interventions in humanitarian settings: Cameroon and DRC. Technical Report. https://doi.org/10.4160/9789290606635

Bang, H. N. (2021). A gap analysis of the legislative, policy, institutional and crises management frameworks for disaster risk management in Cameroon. *Progress in Disaster Science*, *11*, 100190. https://doi.org/10.1016/j.pdisas.2021.100190

Bang, H. N., & Balgah, R. A. (2022). The ramification of Cameroon's Anglophone crisis: conceptual analysis of a looming "Complex Disaster Emergency". *Journal of International Humanitarian Action*, *7*(1), 6.

Bentley, J. W., Andrade-Piedra, J., Demo, P., Dzomeku, B., Jacobsen, K., Kikulwe, E., Kromann, P., Kumar, P. L., McEwan, M., & Mudege, N. (2018). Understanding root, tuber, and banana seed systems and coordination breakdown: a multi-stakeholder framework. *Journal of Crop Improvement*, *32*(5), 599-621. https://doi.org/10.1080/15427528.2018.1476998

Beyene, K. (2015). Destitution, biology, yield loss and management of sweet potato weevils (*Cylas formicaries* (Fabrcius) Insecta: Coleoptera) in Ethiopia. *Journal of Biology, Agriculture and Healthcare*, *5*(22), 65-72.

Buddenhagen, C. E., Hernandez Nopsa, J. F., Andersen, K. F., Andrade-Piedra, J., Forbes, G. A., Kromann, P., Thomas-Sharma, S., Useche, P., & Garrett, K. A. (2017). Epidemic network analysis for mitigation of invasive pathogens in seed systems: Potato in Ecuador. *Phytopathology*, *107*(10), 1209-1218. https://doi.org/10.1094/PHYTO-03-17-0108-FI

Buddenhagen, C. E., Xing, Y., Andrade-Piedra, J. L., Forbes, G. A., Kromann, P., Navarrete, I., Thomas-Sharma, S., Choudhury, R. A., Andersen Onofre, K. F., Schulte-Geldermann, E., Etherton, B. A., Plex Sula, A. I., & Garrett, K. A. (2022). Where to invest project efforts for greater benefit: A framework for management performance mapping with examples for potato seed health. *Phytopathology*, *112*(7), 1431-1443. https://doi.org/10.1094/PHYTO-05-20-0202-R

Buko, D. H., Gedebo, A., Spetz, C., & Hvoslef-Eide, A. K. (2020). An update of sweet potato viral disease incidence and spread in Ethiopia. *African Journal of Agricultural Research*, *16(8)*, 1116-1126. https://doi.org/10.5897/AJAR2020.14918

Canney-Davison, S., Davies, L., & McEwan, M. (2023). Tools4SeedSystems: Working towards resilience through root, tuber and banana crops in humanitarian settings. Workshop Report.

Carvajal-Yepes, M., Cardwell, K., Nelson, A., Garrett, K. A., Giovani, B., Saunders, D., Kamoun, S., Legg, J., Verdier, V., et al. (2019). A global surveillance system for crop diseases. *Science*, *364*(6447), 1237-1239. https://doi.org/10.1126/science.aaw1572

CDP. (2023). *Ethiopia humanitarian crisis*. https://disasterphilanthropy.org/disasters/ethiopia-tigray-crisis/

Csárdi, G., Nepusz, T., Traag, V., Horvát, S., Zanini, F., Noom, D., & Müller, K. (2023). igraph: Network Analysis and Visualization in R. *R package version 1.5.1*. https://doi.org/10.5281/zenodo.7682609

Delaquis, E., Almekinders, C. J., & Andrade-Piedra, J. (2020). Glossary of root, tuber and banana seed systems. RTB User Guide. *RTB User Guide*.

Delaquis, E., Andersen, K. F., Minato, N., Cu, T. T. L., Karssenberg, M. E., Sok, S., Wyckhuys, K. A., Newby, J. C., Burra, D. D., et al. (2018). Raising the stakes: cassava seed networks at multiple scales in Cambodia and Vietnam. *Frontiers in Sustainable Food Systems*, *2*, 73. https://doi.org/10.3389/fsufs.2018.00073

Deloko, D. C. T., Achiangia, N. P., Chofong, N. G., Mbulli, A. I., Anoumaa, M., Sama, L. F., & Fonkou, T. (2021). Prevalence of potato viruses on potato (*Solanum tuberosum* L.) grown in the Western

Highlands of Cameroon. *Journal of Agriculture and Food Research*, *5*, 100192. https://doi.org/10.1016/j.jafr.2021.100192

Dicko, A. (2023). rgeoboundaries: A Client to geoBoundaries, A Political Administrative Boundaries Dataset. https://github.com/wmgeolab/rgeoboundaries

Doungous, O., Masky, B., Levai, D. L., Bahoya, J. A., Minyaka, E., Mavoungou, J. F., Mutuku, J. M., & Pita, J. S. (2022). Cassava mosaic disease and its whitefly vector in Cameroon: Incidence, severity and whitefly numbers from field surveys. *Crop Protection*, *158*, 106017. https://doi.org/10.1016/j.cropro.2022.106017

ECPHAO. (2023). *Cameroon factsheet: European Civil Protection and Humanitarian Aid Operations*. https://civil-protection-humanitarian-aid.ec.europa.eu/where/africa/cameroon_en

Etherton, B., Plex Sula, A., Mouafo-Tchinda, R., Kakuhenzire, R., Kassaye, H., Asfaw, F., Kosmakos, V., McCoy, R., Xing, Y., et al. (2025). Translating Ethiopian potato seed networks: Identifying strategic intervention points for managing bacterial wilt and other diseases. *Agricultural Systems*, *222*, 104167. https://doi.org/https://doi.org/10.1016/j.agsy.2024.104167

Etherton, B. A., Choudhury, R., Alcalá-Briseño, R., Xing, Y., Sulá, A. P., Carrillo, D., Wasielewski, J., Stelinski, L., Grogan, K., et al. (2023). Are avocados toast? A framework to analyze decision-making for emerging epidemics, applied to laurel wilt. *Agricultural Systems*, *206*, 103615. https://doi.org/10.1016/j.agsy.2023.103615

Etherton, B. A., Choudhury, R. A., Alcalá Briseño, R. I., Mouafo-Tchinda, R. A., Plex Sulá, A. I., Choudhury, M., Adhikari, A., Lei, S. L., Kraisitudomsook, N., et al. (2024). Disaster plant pathology: Smart solutions for threats to global plant health from natural and human-driven disasters. *Phytopathology*, *114*(5), 855-868.

FAO. (2021a). *Emergency assistance to improve food and nutrition security of IDPS in South West region of Cameroon*. https://www.fao.org/documents/card/fr/c/CB3577EN/

FAO. (2021b). *The impact of disasters and crises on agriculture and food security*. https://www.fao.org/documents/card/en/c/cb3673en

FAOSTAT. (2021). *Trade: crops and livestock products*. https://www.fao.org/faostat/en/#home

Fogain, R., Mouliom Péfoura, A., Abadie, C., Escalant, J.-V., & Tomekpé, K. (1998). Banana and plantain IPM in Cameroon: progress and problems. Banana IPM workshop November 1998, Nelspruit, Afrique du Sud.

Ford, J. K., Smith, E. M., Weissbein, D. A., Gully, S. M., & Salas, E. (1998). Relationships of goal orientation, metacognitive activity, and practice strategies with learning outcomes and transfer. *Journal of Applied Psychology*, *83*(2), 218.

Foyou, V. E., Ngwafu, P., Santoyo, M., & Ortiz, A. (2018). The Boko Haram insurgency and its impact on border security, trade and economic collaboration between Nigeria and Cameroon: An exploratory study. *African Social Science Review*, *9*(1), 7. https://digitalscholarship.tsu.edu/assr/vol9/iss1/7

Garrett, K., Bebber, D., Etherton, B., Gold, K., Sulá, A. P., & Selvaraj, M. G. (2022). Climate change effects on pathogen emergence: artificial intelligence to translate big data for mitigation. *Annual Review of Phytopathology*, *60*. https://doi.org/10.1146/annurev-phyto-021021-042636

Garrett, K. A. (2021). Impact network analysis and the INA R package: Decision support for regional management interventions. *Methods in Ecology and Evolution*, *12*(9), 1634-1647. https://doi.org/https://doi.org/10.1111/2041-210X.13655

Gibson, R., & Kreuze, J. F. (2015). Degeneration in sweetpotato due to viruses, virus-cleaned planting material and reversion: a review. *Plant Pathology*, *64*(1), 1-15. https://doi.org/10.1111/ppa.12273

Gosling, J. P. (2018). SHELF: the Sheffield elicitation framework. *Elicitation: The science and art of structuring judgement*, 61-93. https://doi.org/https://doi.org/10.1007/978-3-319-65052-4_4

Guchi, E. (2015). Disease management practice on potato (*Solanum tuberosum* L.) in Ethiopia. *World Journal of Agricultural Research*, *3*(1), 34-42.

Hijmans, R. J., Bivand, R., Forner, K., Ooms, J., Pebesma, E., & Sumner, M. D. (2022). Package 'terra'. *Maintainer: Vienna, Austria*.

Hirpa, A., Meuwissen, M. P., Tesfaye, A., Lommen, W. J., Lansink, A. O., Tsegaye, A., & Struik, P. C. (2010). Analysis of seed potato systems in Ethiopia. *American Journal of Potato Research*, *87*(6), 537-552. https://doi.org/10.1007/s12230-010-9164-1

Hunt, M., Chénier, A., Bezanson, K., Nouvet, E., Bernard, C., de Laat, S., Krishnaraj, G., & Schwartz, L. (2018). Moral experiences of humanitarian health professionals caring for patients who are dying or likely to die in a humanitarian crisis. *Journal of International Humanitarian Action*, *3*(1), 1-13. https://doi.org/10.1186/s41018-018-0040-9

IFPRI. (2020). Spatially-Disaggregated Crop Production Statistics Data in Africa South of the Sahara for 2017. *Harvard Dataverse International Food Policy Research Institute*.

IFPRI, I. F. P. R. I. (2024). Global Spatially-Disaggregated Crop Production Statistics Data for 2020 Version 1.0. In: Harvard Dataverse, V3.

International Food Policy Research, I. (2020). *Spatially-disaggregated crop production statistics data in Africa south of the Sahara for 2017, https://doi.org/10.7910/DVN/FSSKBW* [Spatially-disaggregated crop production statistics]. Harvard Dataverse, V2. https://doi.org/doi:10.7910/DVN/FSSKBW

IOM. (2023). *More than 4.38 million people displaced in Ethiopia, more than half due to conflict: New IOM Report*. https://ethiopia.iom.int/news/more-438-million-people-displaced-ethiopia-more-half-due-conflict-new-iom-report

Jacobsen, K., Omondi, B., Almekinders, C., Alvarez, E., Blomme, G., Dita, M., Iskra-Caruana, M. L., Ocimati, W., Tinzaara, W., & Kumar, P. (2019). Seed degeneration of banana planting materials: strategies for improved farmer access to healthy seed. *Plant Pathology*, *68*(2), 207-228. https://doi.org/10.1111/ppa.12958

Jongejans, E., Skarpaas, O., Ferrari, M. J., Long, E. S., Dauer, J. T., Schwarz, C. M., Rauschert, E. S., Jabbour, R., Mortensen, D. A., & Isard, S. A. (2015). A unifying gravity framework for dispersal. *Theoretical Ecology*, *8*(2), 207-223. https://doi.org/10.1007/s12080-014-0245-5

Keshav, K., Plex-Sula, A., & Garrett, K. (2024). geohabnet: Geographical Risk Analysis Based on Habitat Connectivity. *CRAN*, *version 2.0.0*. https://garrettlab.github.io/HabitatConnectivity/

Konje, C., Abdulai, A., Tange, A. D., Tarla, D., & Tita, M. A. (2019). Identification and management of pests and diseases of garden crops in Santa, Cameroon. *Journal of Agriculture and Ecology Research International*, *18*(2), 1-9. https://doi.org/10.9734/JAERI/2019/v18i230055

Macrotrends. (2023). *Cameroon Refugee Statistics 1970-2023*. https://www.macrotrends.net/countries/CMR/cameroon/refugee-statistics

Margosian, M. L., Garrett, K. A., Hutchinson, J. S., & With, K. A. (2009). Connectivity of the American agricultural landscape: assessing the national risk of crop pest and disease spread. *BioScience*, *59*(2), 141-151. https://doi.org/10.1525/bio.2009.59.2.7

Mbah, L. T., Molua, E. L., Bomdzele, E., & Egwu, B. M. (2023). Farmers' response to maize production risks in Cameroon: An application of the criticality risk matrix model. *Heliyon*, *9*(4). https://doi.org/10.1016/j.heliyon.2023.e15124

McGuire, S. J., & Sperling, L. (2008). Leveraging farmers' strategies for coping with stress: seed aid in Ethiopia. *Global Environmental Change*, *18*(4), 679-688.

Meno, L., Escuredo, O., Rodríguez-Flores, M. S., & Seijo, M. C. (2020). Modification of the TOMCAST model with aerobiological data for management of potato early blight. *Agronomy*, *10*(12), 1872.

Navarrete, I., López, V., Andrade-Piedra, J. L., Almekinders, C. J., Kromann, P., & Struik, P. C. (2022). Agroecological settings and seed recycling account only partially for potato seed degeneration in Ecuador. *Agronomy for Sustainable Development*, *42*(6), 109. https://doi.org/10.1007/s13593-022-00840-1

Nduwimana, I., Sylla, S., Xing, Y., Simbare, A., Niyongere, C., Garrett, K. A., & Bonaventure Omondi, A. (2022). Banana seed exchange networks in Burundi–Linking formal and informal systems. *Outlook on Agriculture*, *51*(3), 334-348. https://doi.org/10.1177/00307270221103288

Ngatat, S., Hanna, R., Lienou, J., Ghogomu, R. T., Nguidang, S. P. K., Enoh, A. C., Ndemba, B., Korie, S., Fotso Kuate, A., & Nanga Nanga, S. (2022). Musa germplasm A and B genomic composition differentially affects their susceptibility to banana bunchy top virus and its aphid vector, Pentalonia nigronervosa. *Plants*, *11*(9), 1206. https://doi.org/10.3390/plants11091206

O'Hagan, A. (2019). Expert knowledge elicitation: subjective but scientific. *The American Statistician*, *73*(sup1), 69-81. https://doi.org/10.1080/00031305.2018.1518265

OCHA. (2022). *Cameroon multi-stakeholder dialogue on refugees*. https://reliefweb.int/report/cameroon/cameroon-multi-stakeholder-dialogue-refugees-november-2022

OCHA. (2023a). *Cameroon humanitarian needs overview 2023*. https://www.unocha.org/publications/report/cameroon/cameroon-humanitarian-needs-overview-2023-march-2023

OCHA. (2023b). *Ethiopia: humanitarian needs overview 2023*. https://reliefweb.int/report/ethiopia/ethiopia-humanitarian-needs-overview-2023

Okolle, J. N., Fansi, G. H., Lombi, F. M., Sama Lang, P., & Loubana, P. M. (2009). Banana entomological research in Cameroon: how far and what next. *The African Journal of Plant Science and Biotechnology*, *3*(1), 1-19.

Pedersen, T. L. (2022). ggraph: An Implementation of Grammar of Graphics for Graphs and Networks. *Retrieved January*, *1*, 2018. https://CRAN.R-project.org/package=ggraph

Petsakos, A., Prager, S. D., Gonzalez, C. E., Gama, A. C., Sulser, T. B., Gbegbelegbe, S., Kikulwe, E. M., & Hareau, G. (2019). Understanding the consequences of changes in the production frontiers for roots, tubers and bananas. *Global Food Security*, *20*, 180-188. https://doi.org/10.1016/j.gfs.2018.12.005

Plex Sulá, A. I., De Col, V., Etherton, B. A., Xing, Y., Agarwal, A., Ramić, L., Bonaiuti, E., Friedmann, M., Proietti, C., & Thiele, G. (2024). What traits of collaboration networks are associated with project success? The case of two CGIAR agricultural research programs for development. *Agricultural Systems*, *219*, 104013.

Poubom, C., Awah, E., Tchuanyo, M., & Tengoua, F. (2005). Farmers' perceptions of cassava pests and indigenous control methods in Cameroon. *International Journal of Pest Management*, *51*(2), 157-164. https://doi.org/10.1080/09670870500131863

Prasanna, B. M., Carvajal-Yepes, M., Kumar, P. L., Kawarazuka, N., Liu, Y., Mulema, A. A., McCutcheon, S., & Ibabao, X. (2022). Sustainable management of transboundary pests requires holistic and inclusive solutions. *Food Security*, *14*(6), 1449-1457.

Raleigh, C., Linke, R., Hegre, H., & Karlsen, J. (2010). Introducing ACLED: An armed conflict location and event dataset. *Journal of Peace Research*, *47*(5), 651-660. https://doi.org/10.1177/022234331037891

RBA. (2022). *Agriculture performance assessment of 2022 meher season. Regional bureaus of agriculture (Amhara, Oromia, SNNPR and Sidama).* https://panorama.solutions/en/organisation/regional-bureaus-agriculture-amhara-oromia-tigray-and-snnpr

Savary, S., Willocquet, L., Pethybridge, S. J., Esker, P., McRoberts, N., & Nelson, A. (2019). The global burden of pathogens and pests on major food crops. *Nature Ecology & Evolution*, *3*(3), 430-439. https://doi.org/10.1038/s41559-018-0793-y

Scott, G. J. (2021). A review of root, tuber and banana crops in developing countries: past, present and future. *International Journal of Food Science & Technology*, *56*(3), 1093-1114. https://doi.org/10.1111/ijfs.14778

Sperling, L. (2008). *When disaster strikes: a guide to assessing seed system security*. CIAT.

Sperling, L., & Almekinders, C. J. (2023). Informal Commercial Seed Systems: Leave, Suppress or Support Them? *Sustainability*, *15*(18), 14008. https://doi.org/10.3390/su151814008

Sperling, L., Deressa, A., Assefa, S., Assefa, T., McGuire, S. J., Amsalu, B., Negusse, G., Asfaw, A., Mulugeta, W., Dagne, B., Hailemariam, G., Tenaye, A., Teferra, B., Anchala, C., Admassu, H., Tsehaye, H., Geta, E., Dauro, D., & Molla, Y. (2007). Long-term seed aid in Ethiopia: Past, present and future perspectives. 141. http://hdl.handle.net/10625/43569

Sperling, L., Gallagher, P., McGuire, S., March, J., & Templer, N. (2020). Informal seed traders: the backbone of seed business and African smallholder seed supply. *Sustainability*, *12*(17), 7074.

Sperling, L., & McGuire, S. (2010). Understanding and strengthening informal seed markets. *Experimental Agriculture*, *46*(2), 119-136. https://doi.org/10.1017/S0014479709991074

Sperling, L., Mottram, A., Ouko, W., & Love, A. (2022). Seed emergency response tool: Guidance for practitioners. *Produced by Mercy Corps and SeedSystem. org as a Part of the ISSD Africa Activity*.

Tang, F. H., Nguyen, T. H., Conchedda, G., Casse, L., Tubiello, F. N., & Maggi, F. (2024). CROPGRIDS: a global geo-referenced dataset of 173 crops. *Scientific Data*, *11*(1), 413.

Tesfaye, T., Feyissa, T., & Abraham, A. (2011). Survey and serological detection of sweet potato (Ipomoea batatas (L.) Lam) viruses in Ethiopia. *Journal of Applied Biosciences*, *41*, 2746-2756.

Tessema, G. L., & Seid, H. E. (2023). Potato bacterial wilt in Ethiopia: history, current status, and future perspectives. *PeerJ*, *11*, e14661. https://doi.org/10.7717/peerj.14661

TGHAT. (2022). *Tigray bureau of agriculture and natural resources, emergency and recovery support plan for the 2022/23 budget year, October 2022*. https://www.tghat.com/2023/01/12/government-of-tigray-bureau-of-agriculture-natural-resources-emergency-and-recovery-plan/

Thiele, G., Khan, A., Heider, B., Kroschel, J., Harahagazwe, D., Andrade, M., Bonierbale, M., Friedmann, M., Gemenet, D., & Cherinet, M. (2017). Roots, tubers and bananas: planning and research for climate resilience. *Open Agriculture*, *2*(1), 350-361. https://doi.org/10.1515/opag-2017-0039

Thomas-Sharma, S., Andrade-Piedra, J., Carvajal Yepes, M., Hernandez Nopsa, J., Jeger, M., Jones, R., Kromann, P., Legg, J., Yuen, J., & Forbes, G. (2017). A risk assessment framework for seed degeneration: Informing an integrated seed health strategy for vegetatively propagated crops. *Phytopathology*, *107*(10), 1123-1135. https://doi.org/10.1094/PHYTO-09-16-0340-R

Thomas-Sharma, S., Abdurahman, A., Ali, S., Andrade-Piedra, J., Bao, S., Charkowski, A., Crook, D., Kadian, M., Kromann, P., & Struik, P. C. (2016). Seed degeneration in potato: the need for an integrated seed health strategy to mitigate the problem in developing countries. *Plant Pathology*, *65*(1), 3-16. https://doi.org/10.1111/ppa.12439

Tize, I., Fotso, A. K., Nukenine, E. N., Masso, C., Ngome, F. A., Suh, C., Lendzemo, V. W., Nchoutnji, I., Manga, G., & Parkes, E. (2021). New cassava germplasm for food and nutritional security in Central Africa. *Scientific Reports*, *11*(1), 7394. https://doi.org/10.1038/s41598-021-86958-w

USAID. (2022). Strategic framework for early recovery, risk reduction, and resilience (ER4). https://www.usaid.gov/sites/default/files/2023-01/ER4_Framework-10.13.2022.pdf

Vasantha Raju, N., & Harinarayana, N. (2016). Online survey tools: A case study of Google Forms. National conference on scientific, computational & information research trends in engineering, GSSS-IETW, Mysore,

Wickham, H. (2016). ggplot2: Elegant Graphics for Data Analysis. *Springer-Verlag New York*, *3*(2), 180-185. https://ggplot2.tidyverse.org

Wiebe, K., Zurek, M., Lord, S., Brzezina, N., Gabrielyan, G., Libertini, J., Loch, A., Thapa-Parajuli, R., Vervoort, J., & Westhoek, H. (2018). Scenario development and foresight analysis: exploring options to inform choices. *Annual Review of Environment and Resources*, *43*, 545-570. https://doi.org/10.1146/annurev-environ-102017-030109

Wubaye, G. B., Gashaw, T., Worqlul, A. W., Dile, Y. T., Taye, M. T., Haileslassie, A., Zaitchik, B., Birhan, D. A., Adgo, E., & Mohammed, J. A. (2023). Trends in rainfall and temperature extremes in Ethiopia: Station and agro-ecological zone levels of analysis. *Atmosphere*, *14*(3), 483. https://doi.org/10.3390/atmos14030483

Xing, Y., Hernandez Nopsa, J. F., Andersen, K. F., Andrade-Piedra, J. L., Beed, F. D., Blomme, G., Carvajal-Yepes, M., Coyne, D. L., Cuellar, W. J., Forbes, G. A., Kreuze, J. F., Kroschel, J., Kumar, P. L., Legg, J. P., Parker, M., Schulte-Geldermann, E., Sharma, K., & Garrett, K. A. (2020). Global Cropland Connectivity: A Risk Factor for Invasion and Saturation by Emerging Pathogens and Pests. *BioScience*, *70*(9), 744-758. https://doi.org/10.1093/biosci/biaa067