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

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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. Experts reported imports of cassava seed to Cameroon, which pose a risk to cassava production in Cameroon if the cuttings inadvertently introduce seedborne pathogens. 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 banana (*Musa* spp.) suckers, cassava (*Manihot esculenta*) stakes, potato (*Solanum tuberosum*) tubers, and sweetpotato (*Ipomoea batatas*) vines. 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 (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, cultural traditions, or simply lack of infrastructure or awareness of seed health concerns, can deter growers, even when formal sector seed may be available. In this study, we focus on seed systems of

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

1.2 Ongoing disasters and humanitarian needs in Cameroon and Ethiopia

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

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

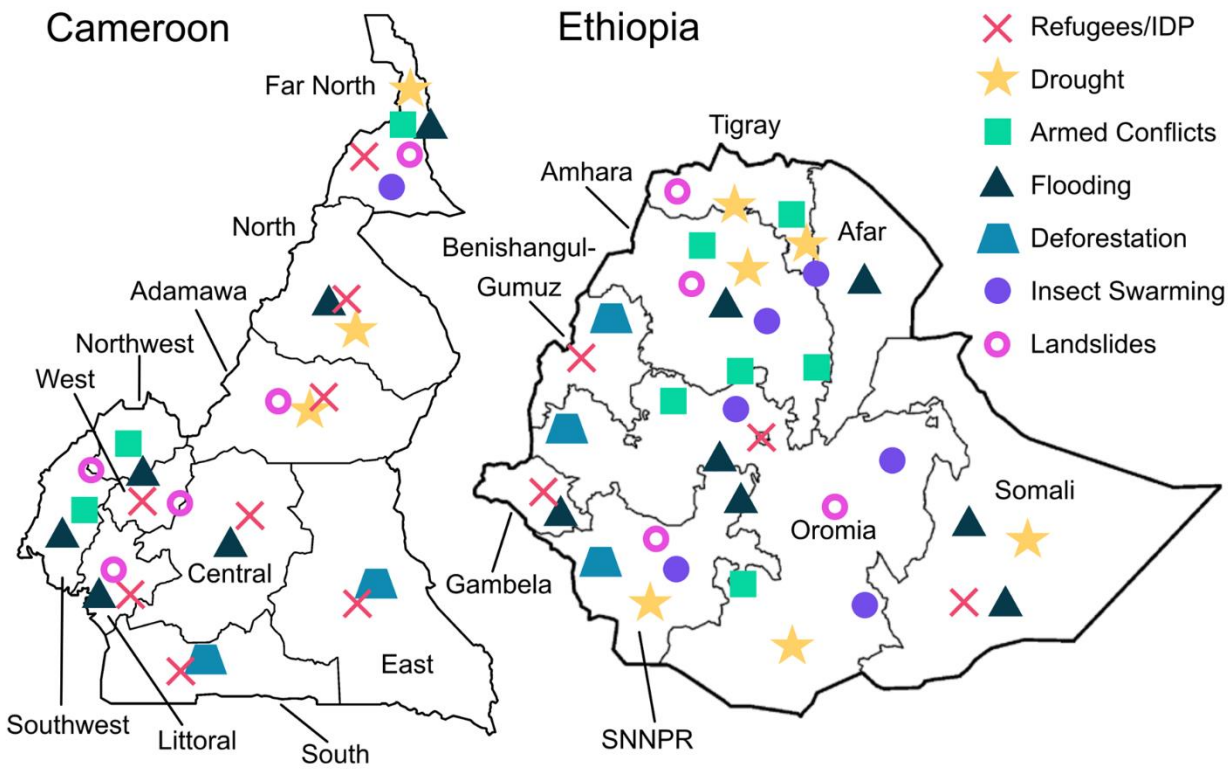

Figure 1. Maps of Cameroon and Ethiopia indicating representative types of disaster and humanitarian issues such as major conflicts that affect agricultural production. For example, red 'X's represent refugee issues and/or internally displaced people (IDP). These icons are placed approximately and do 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.

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).

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 (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 pathogen and pest information, that could support a national plant health risk analysis, highlights the importance of rapid risk assessment tools that identify regions likely to be important in pathogen and pest

spread, target economically important pathogens and pests, and assess the potential role of informal trade in pathogen and pest spread (Carvajal-Yepes et al., 2019; Thomas-Sharma et al., 2017; Xing et al., 2020). This information can help in identifying risks for consideration in emergency seed assistance and planning longer-term agricultural development strategies.

1.4 The objectives and approaches of this study

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

Versions of these analyses are part of ongoing development of the Rapid Risk assessment for Mitigation of plant pathogens and pests (R2M) toolbox (garrettlab.com/r2m/).

2.1 Cropland connectivity for host-specific pathogens and pests

We analyzed cropland connectivity to map locations likely to be important in outbreaks of host-specific pathogens and pests in Cameroon and Ethiopia. Cropland connectivity analyses evaluate potential

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

236 Gravity models also incorporate the role of distance, where movement is more likely between
237 closer locations (nodes). We used the gravity model $M_i M_j d_{ij}^{-\beta}$, where M_i and M_j represent the harvested
238 crop area of two nodes i and j. The first gravity model used the inverse power law dispersal kernel $d_{ij}^{-\beta}$,
239 where d_{ij} represents the distance between nodes i and j, and β indicates the likelihood of pathogen
240 movement across that distance (Andersen Onofre et al., 2021; Xing et al., 2020). We also used the gravity
241 model $M_i M_j e^{-\gamma d_{ij}}$, with the dispersal kernel based on the negative exponential model, where γ indicates
242 the likelihood of pathogen movement. The distance between two locations (nodes) was calculated using
243 the terra package in R (version 1.7-71) (Hijmans et al., 2022), a geographical spatial data analysis package.
244 The relative likelihood of pathogen movement between two nodes i and j for $\beta = 1$ is higher than for
245 $\beta = 2$; 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 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 took the mean at each geographic pixel across the results from all parameter combinations, to provide a general CCRI for each location. That is, the value mapped at each location in the general summary map is

269 the weighted mean of centrality metrics (the CCRI) averaged across all parameter combinations in the
270 sensitivity analysis. Higher CCRI scores indicate locations that are more likely to play an important role in
271 an epidemic or invasion based on host availability, pathogen or pest dispersal, and proximity to other
272 crop production.

273 ## 2.2 Expert knowledge elicitation

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

282 The first stage of survey development was to review the content of the country- and crop-specific
283 surveys with the organizing team to make sure they were appropriately matched to the situation in each
284 country. The surveys focused on RTB pathogens and pests causing high yield loss, with potentially
285 important impacts on vulnerable human populations. In Cameroon, four surveys covered banana,
286 cassava, potato and sweetpotato. Similarly, two surveys were designed for experts in Ethiopia, focusing
287 on potato and sweetpotato. Surveys were deployed using Google Forms (Vasantha Raju & Harinarayana,
288 2016). Crop-specific experts who had some insights into seed systems participated in one-day workshops
289 in November 2022 in Yaoundé, Cameroon, and in March 2023 in Addis Ababa, Ethiopia. In Cameroon, we
290 recruited 18 experts for cassava, 13 for potato, 10 for banana and 7 for sweetpotato. In Ethiopia, we
291 recruited 20 experts for potato, and 9 for sweetpotato. Experts known through previous collaboration

292 with CGIAR and the University of Florida were selected based on their experience with RTB crops,
293 representing governmental organizations, the private sector, NGOs, National Agricultural Research and
294 Extension Systems (NARES), and CGIAR centers (IITA, CIP, and Alliance Biodiversity-CIAT). Across crops
295 and locations, 60 to 78% of participating experts identified as seed system experts in Cameroon or seed
296 system/breeding experts in Ethiopia. Anonymized information about the experts' experience in each state
297 or region and each crop, along with all crop-specific responses, are available upon request. Participating
298 experts completed the surveys individually, for the crop for which they had expertise. Experts were first
299 asked to provide their years of experience in each region or state in their country of expertise. In each
300 survey, experts were then asked to identify the major pests and diseases, identify the informal trade
301 routes for seed in the country and with neighboring countries, estimating crop-system specific
302 parameters.

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

316 and banana. Note that an important caveat for comparison of locations is that locations with less crop
317 production tend to have less attention by experts, so lower expert experience in a region in a sense
318 represents 'lower sampling effort'; that is, regions and regional states where experts have less experience
319 will tend to have lower numbers of pathogen and pest species reported. Visualizations for each crop
320 indicate whether at least one expert reported each pest or pathogen in each region or state, and the
321 corresponding relative confidence for the region or state based on the total years of expert experience
322 for the region or state.

323 ## 2.3 Within-country informal seed trade in Cameroon

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

336 ## 2.4 Trade with neighboring countries: Informal seed trade and food commodity trade

337 Experts were asked about informal trade of potato, sweetpotato, cassava and banana seed with
338 neighboring countries. Experts indicated which countries they thought informally imported seed from and

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

348 Trade in food commodities generally represents a lower risk for the spread of pathogens and
349 pests compared to trade in planting materials, but can also be a factor if effective phytosanitary measures
350 are not in place. For crops like potato trade in food commodities is a higher risk, because tubers that are
351 imported as food may later be used as seed; planting of food commodities is more unusual for
352 sweetpotato, and not a risk for cassava and banana. For the analysis of food commodity trade, FAO import
353 and export data were analyzed for Cameroon, Ethiopia, and their respective neighboring countries
354 (FAOSTAT, 2021). Here, the FAO data represents the trade of food, or “trade that occurs within a legal
355 framework and is obtained from certified governmental distributors.” Products manufactured by roasting
356 or sterilization were excluded in this trade data, because of their reduced risk. FAO trade data were
357 assembled for each crop, where the trade volume (in tons) between each pair of countries was averaged
358 for 2006-2020 (FAOSTAT, 2021). The trade volumes were then rescaled to represent the proportion of
359 crop-specific trade for a country. For example, if Ethiopia exported on average 300 kg of potato to
360 Djibouti, where the most exported was 1000 kg, the link weight would be 0.3. The FAO food trade data
361 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, 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

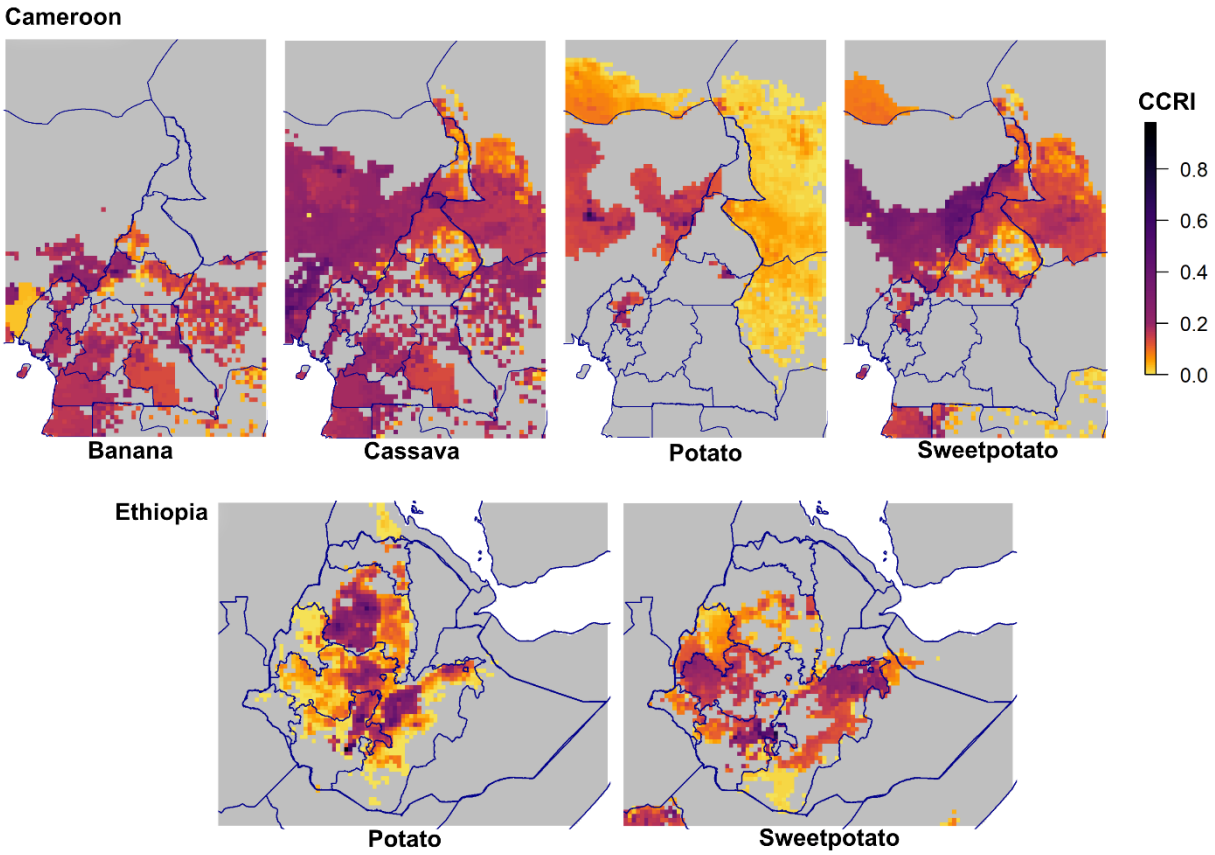

Figure 2. Maps of cropland connectivity risk indices for banana, cassava, potato, and sweetpotato in Cameroon and for potato and sweetpotato in Ethiopia. The cropland connectivity risk index is based on networks of potential spread of a crop-specific pathogen or pest across a landscape of crop hosts; locations with higher cropland connectivity are likely to be more important for pathogen and pest establishment and spread, based on host availability.

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

3.2 Expert knowledge elicitation: Pathogen and pest communities

Experts noted locations where they knew pathogens and pests were present. Here, absence of evidence is not evidence of absence, but locations noted by experts are generally more well-known to have important problems with pathogens and pests. For banana in Cameroon, experts had the most experience in the Centre region, followed by the South, Littoral, and then the East and Northwest regions. The list of pathogens and pests noted by experts was longest in the South zone with at least eight major

pests and pathogens. Anthracnose (caused by *Colletotrichum musae*) was noted present in most regions of Cameroon, and burrowing nematodes and yellow sigatoka were noted present in many regions. Banana seed degeneration in Cameroon was noted by experts to be associated with many pathogens/diseases and pests, including the burrowing nematode, BBTV, banana weevil, anthracnose, and rhizome soft rot (caused by *Pectobacterium*).

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

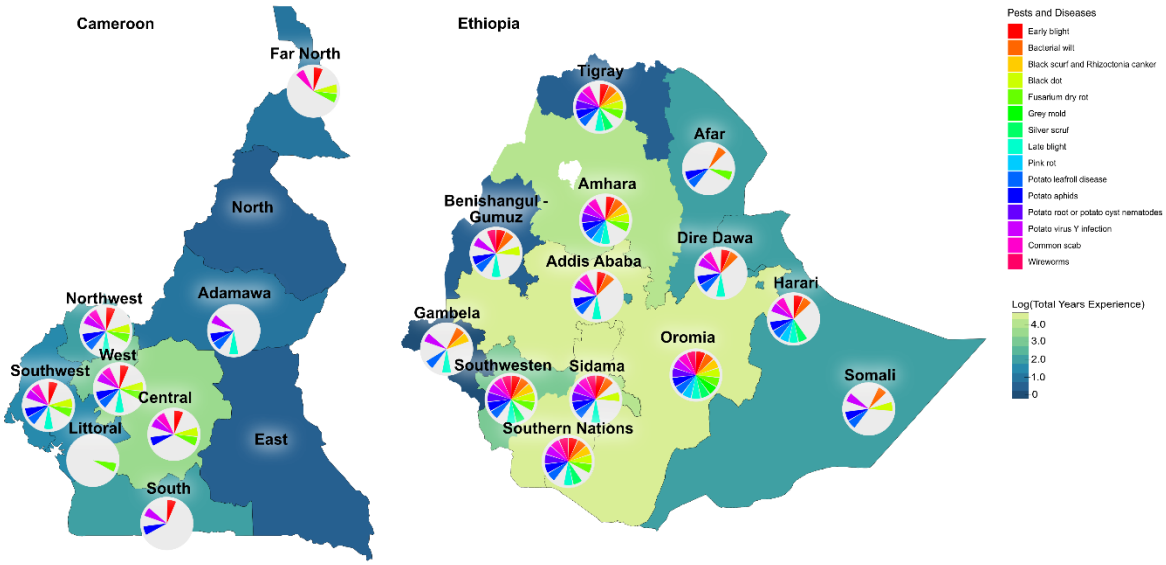

Figure 3. The major potato pests and pathogens noted in expert knowledge elicitation for Cameroon and Ethiopia (based on Ethiopian states as of March 2023). The color in a region or state is proportional to the log-transformed sum of the years of experience reported by the experts for potato in that 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.**

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

For Ethiopian sweetpotato, southern zones were noted by experts to have the highest pest and pathogen communities, with Sidama and the former SNNPR both noted as having at least 8 pathogens. Alternaria blight and the sweetpotato weevil were noted as present in most regions across Ethiopia.

Experts selected the key causes of seed degeneration as sweetpotato viruses, sweetpotato weevil, *Alternaria bataticola*, and sweetpotato aphids.

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

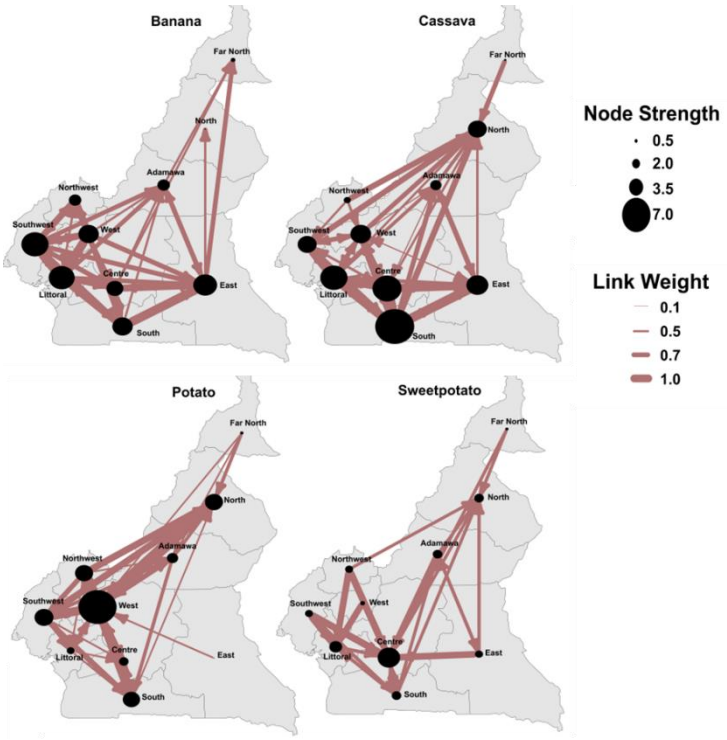

Figure 4. Informal seed trade networks between regions in Cameroon as noted in expert knowledge elicitation. Node size is proportional to node strength, the sum of link weights. Link weights are the proportion of experts who reported the occurrence of informal trade between the linked regions. This study 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.

We analyzed the network of seed transfers between regions in Cameroon as noted by experts for potato and sweetpotato, to assess the risk of pathogen and pest spread through seed between regions. For informal potato and sweetpotato seed trade in Cameroon, all the regions were reported to be interconnected. There was high node strength for seed trade reported in the West region for potato (77%

435 of experts noting trade) and in the Centre and Littoral regions for sweetpotato (43% of experts noting
436 trade) **(Figure 4).**

437 For banana and cassava in Cameroon, regions were reported to be well linked. Experts noted high
438 regional informal seed trade strength for banana in the Southwest, Littoral, East, West and South regions
439 for cassava in the South, Centre, Littoral, West and East regions **(Figure 4).** The experts also reported that,
440 due to the current crisis in the Northwest and Southwest regions of Cameroon and the conflict with Boko
441 Haram in the Far-North region, growers have moved to other regions and neighboring countries with their
442 goods, including food and/or seed. Experts also highlighted the vulnerable situation of many of these
443 growers working in neighboring regions and countries.

444 **3.4 Informal seed trade with neighboring countries**

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

448 For informal trade of banana seed in Cameroon, 40% of experts (4) noted exports to Gabon, and
449 30% (3) noted imports from Gabon and exports to Nigeria **(Figure 5, I)**. Cameroon was noted to receive
450 imports from Nigeria, the Central African Republic, and Congo Republic, and noted to informally export to
451 Chad, Nigeria, Central African Republic, Equatorial Guinea, and Congo Republic.

452 For informal cassava seed trade in Cameroon, 72% of experts (13) noted exports to Gabon, and
453 50% (9) noted imports from Nigeria **(Figure 5, I)**. Informal imports and exports were noted by experts for
454 all neighboring countries, with the exception of informal imports from Chad **(Figure 5, I)**.

455 For informal potato seed trade in Cameroon, 38% of experts (5) noted informal imports from
456 Nigeria to Cameroon, and 30% (4) noted informal export from Cameroon to Gabon **(Figure 5, I)**. Informal

exports and imports of potato seed between all neighboring countries and Cameroon was noted by at

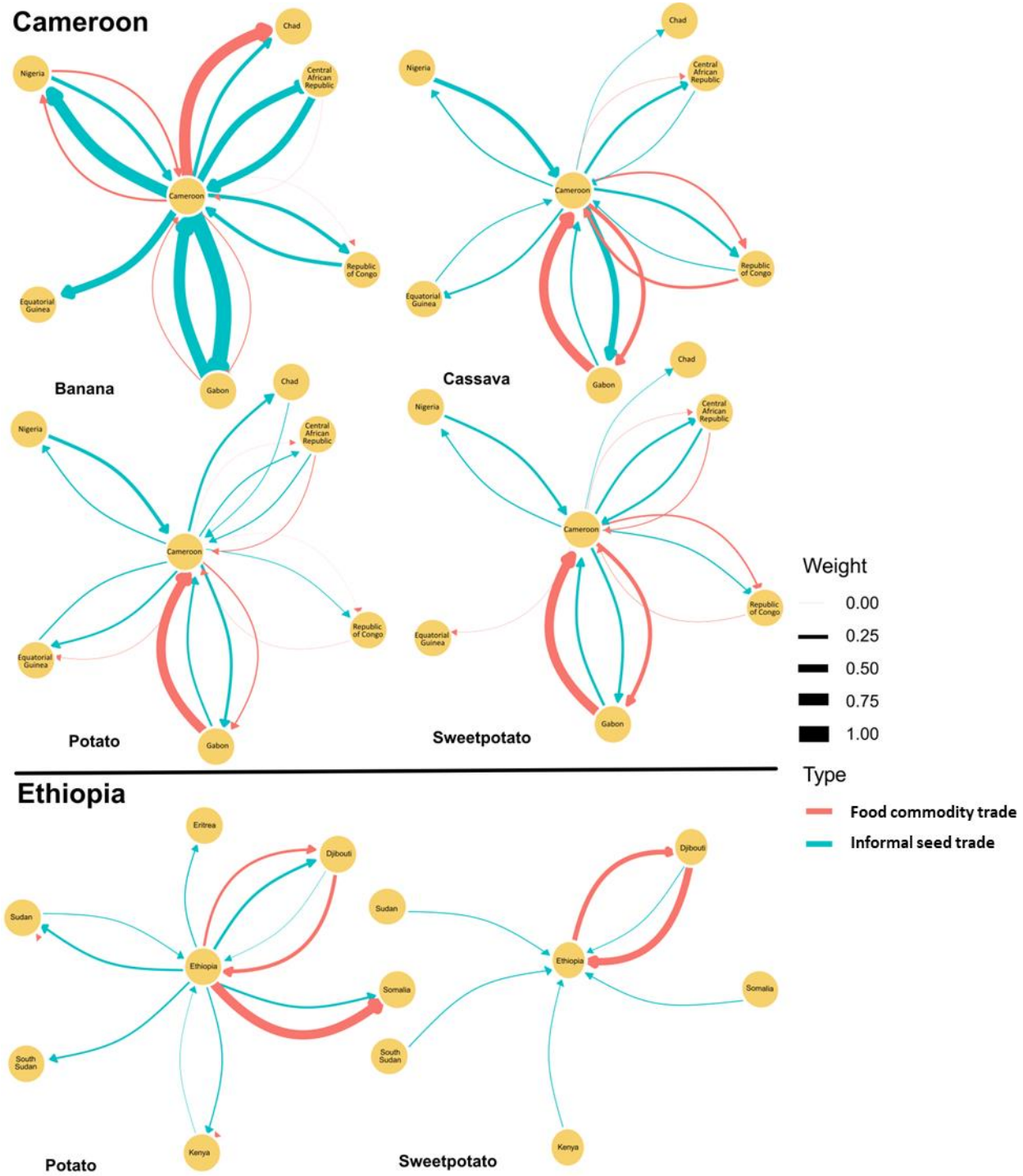

Figure 5. Informal seed trade networks (blue links) noted in expert knowledge elicitation, and food commodity trade networks (red links; FAO trade databases for 2006-2020), with neighboring countries for Cameroon and Ethiopia. Link width for informal seed trade is proportional to the relative confidence 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 is most important as a risk factor pathogen or pest spread for potato, since ware potato can be used as seed.

458 least one expert, with the exception of imports from the Republic of Congo.

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

465 For the informal Ethiopian potato seed trade, 30% of experts (6) noted export to Djibouti, and
466 25% (5) noted exports to Somalia and Sudan **(Figure 5, II)**. No experts noted informal imports from
467 Somalia, Eritrea, and South Sudan. Informal exports were noted for all neighboring countries. Informal
468 trade of sweetpotato seed was reportedly rare from Ethiopia, where no informal exports of sweetpotato
469 seed were noted **(Figure 5, II)**. Informal imports were noted from all neighboring countries except Eritrea,
470 with only 11% of experts (1) noting these imports.

471 **3.5 Food commodity trade with neighboring countries**

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

476 The highest volume trade for Cameroon in banana fruit was exports to Chad, and secondly to
477 Nigeria. Cameroon exported to the Central African Republic and Equatorial Guinea, and imported from
478 the Central African Republic and Gabon **(Figure 5, I)**. For trade of cassava tubers in Cameroon, FAO
479 reported the highest trade volume occurring as imports from Gabon. Imports were also from Republic of
480 Congo, and exports were to the Central African Republic, Gabon, and the Congo Republic **(Figure 5, I)**. For

481 Cameroonian trade in ware potato, exports and imports were reported with the Republic of Congo, the
482 Central African Republic, and Gabon, with the highest trade volume average as imports from Gabon.
483 Cameroon was reported to export to, but received no imports from, Equatorial Guinea. For the trade in
484 sweetpotato roots for consumption, the highest trade volume occurred as Gabon exports to Cameroon.
485 Bidirectional trade occurred between Cameroon and Gabon, the Central African Republic, and the Congo
486 Republic, and exports occurred to Equatorial Guinea. No trade was reported to occur with Chad **(Figure 5,**
487 **I)**. However, in post hoc discussions, an expert in Cameroon reported observing large volumes of roots
488 shipped from Cameroon to Chad daily, an illustration of how expert knowledge can supplement FAO
489 reports.

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

495 4 Discussion

496 4.1 Components of this baseline national plant health risk analysis

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

504 between plant pathology research outputs and decision-making by humanitarian and development
505 organizations.

506 The spread of crop pathogens and pests is driven by a complex interplay of factors including
507 environmental conduciveness to pathogen and pest reproduction, natural and human-driven disasters ,
508 the formal and informal movement of planting material and harvested products, as well as the density
509 and connectivity of crops (Andersen Onofre et al., 2021; Buddenhagen et al., 2022; Garrett et al., 2022;
510 Margosian et al., 2009; Nduwimana et al., 2022; Xing et al., 2020). Many actors may inadvertently
511 contribute to pathogen and pest movement: growers sharing seed, traders selling local seed, general crop
512 traders, and humanitarian groups and governments providing emergency or developmental assistance.
513 Cropland connectivity analyses (**Figure 2**) identify locations likely to be important for the establishment
514 and spread of crop-specific pathogens and pests, based on crop host availability (Margosian et al., 2009;
515 Xing et al., 2020). All else being equal, locations with more crop production are generally more important
516 in epidemics or invasions, for the buildup and spread of pathogens and pests through local trade, spore
517 dispersal, insect flight, etc. Cropland connectivity analysis adds to that idea by accounting for the
518 geographic distribution of production, such that isolated production is less important in epidemics while
519 'bridges' between production areas are likely to be more important. (Buddenhagen et al., 2022). More
520 direct information about trade fills in other dimensions of the potential for pathogen and pest movement
521 (**Figures 4 and 5**).

522 The current distribution of pathogens and pests is key for identifying farmers' most important
523 problems and for understanding the potential spread of pathogens and pests to locations where they are
524 currently absent or rare (**Figure 3**). Expert knowledge elicitation has been used in other systems to
525 evaluate phytosanitary risk, for example by Andersen Onofre et al. (2021) to identify phytosanitary
526 strategies for protecting potato seed systems in the Republic of Georgia. In a study linked to the one
527 reported here, Etherton et al. (2024a) created risk maps for potato seed systems in Ethiopia and evaluated

528 regions at a high risk for pests and diseases, particularly *Ralstonia solanacearum*. Expert knowledge
529 elicitation was also used to evaluate the informal trade network for seeds, and the risk of pathogen and
530 pest spread between regions.

531 **4.2 Ongoing improvement of a national plant health risk analysis**

532 When resources are available, there are many possibilities for improving on this baseline national
533 plant health risk analysis (**Figure 6**). For example, the cropland connectivity analyses represent a simplified
534 view of the risk of spread by averaging across potential dispersal parameters, to represent many potential
535 pathogens and pests. When dispersal is well-characterized for a particular pathogen or pest species, the
536 cropland connectivity analysis can be implemented specifically for that species, and potentially expanded
537 to a fuller habitat connectivity analysis (Keshav et al., 2024), including other geographic traits such as
538 environmental conduciveness to the species. The cropland connectivity analysis may also be improved as
539 crop density maps improve in quality (IFPRI, 2024; Tang et al., 2024). Cropland connectivity analyses can
540 also be a first step for scenario analyses for evaluating regional pest and disease management strategies,
541 by providing an estimate of the potential epidemic or invasion network for simulation experiments in
542 scenario analyses (Etherton et al., 2023; Garrett, 2021; Wiebe et al., 2018).

543 Expert knowledge elicitation can provide a baseline summary of expert perceptions, for ongoing
544 improvement as new information becomes available. Experts have gaps in their knowledge, leading to
545 incomplete or biased information. Experts may tend to have less knowledge about locations where a
546 particular crop is less commonly produced, so that there is less 'experiential sampling effort' in those
547 locations, in terms of expert knowledge. When resources are available for monitoring of pathogens and
548 pests or trade, new information can supplement summaries of expert knowledge. Expert opinion,
549 although potentially biased, is still useful, and can serve as the basis for further statistical inference, such
550 as in a Bayesian statistical analysis which use expert knowledge about a parameter (for example, pest

abundance) in the prior distribution (Ford et al., 1998; O'Hagan, 2019). In this study, we incorporate link weights indicating the relative confidence level across experts. After experts consider responses individually, discussion in small groups, as in methods like the Sheffield protocol for expert knowledge elicitation, can help refine expert opinions (Gosling, 2018; O'Hagan, 2019).

Two points for improvement to the formulation of questions for experts became apparent in this study. First, greater detail about the prevalence of pathogens and pests would be useful, in addition to presence/absence data, along with consideration of what experts anticipate could be emerging pathogens and pests in the near future. Second, the baseline information reported here addresses whether seed movement between locations occurs. Future evaluations could build on this by clarifying how frequent long-distance movement of perishable vegetative planting material is. The level of long-distance trade within a country is an important question from an epidemiological standpoint: long-distance pathogen movement can play a particularly important role in pathogen invasions across diverse regions. In post hoc discussions, some experts thought that information about seed flow and trade networks was not common among crop and seed experts, so that there may be higher uncertainty associated with seed trade networks estimated using expert knowledge elicitation. Targeted follow-up studies addressing the quantity of seed moved through networks would be needed to decrease uncertainty.

A national plant health risk analysis could also benefit from additional information and from links to larger and more general studies (Plex Sulá et al. 2025). For example, yield loss is an important component of risk, but detailed yield loss estimates are expensive. Savary et al. (2019) used an expert survey to estimate global yield losses due to pathogens and pests for five major food security crops, including potato. Information about the geographic distribution of current yield loss to pathogens and pest, and of management strategies adopted, is another potentially valuable component; these are also candidates for expert knowledge elicitation because experts with field experience often have useful knowledge but direct field surveys across large geographic areas are expensive to implement. Expert

575 knowledge elicitation and habitat connectivity analysis are part of the developing R2M toolbox for rapid
576 risk assessment to support mitigation of plant pathogens and pests (garrettlab.com/r2m), designed for
577 continual improvement based on lessons learned in applications across countries and crop systems.
578 Related tools focusing on seed systems include the seed emergency response tool (Sperling et al., 2022),
579 the multi-stakeholder framework for RTB seed systems (Bentley et al., 2018), and other components of
580 the CGIAR tools4seedsystems toolbox (Andrade-Piedra et al., 2023). These tools can be used in
581 conjunction and incorporated into comprehensive risk management frameworks. National or regional
582 analyses can ultimately be integrated in projects such as the Global Plant Health Assessment (Acuña et al.,
583 2023), the proposed Global Surveillance System for Plant Disease (Carvajal-Yepes et al., 2019; Prasanna et
584 al., 2022), and databases such as the CABI digital library (https://www.cabidigitallibrary.org/) .
585 Improvements can continually be made, in terms of the overall quality of data and modeling, and also in
586 terms of the quality of translation for use in humanitarian applications.

587 **4.3 Translating a national plant health risk analysis to support humanitarian activities**

588 National plant health risk analyses can help to identify the most vulnerable cropping regions, and
589 regions likely important for disease establishment or spread. These analyses are intended as input to
590 support decision-making to shape aid policies in response to crises and to prioritize considerations in
591 humanitarian implementation on the ground, including for those along the informal trade chains, such as
592 growers, traders, and seed producers. During times of crisis, first-order humanitarian aid should clearly be
593 allocated to providing affected people with basic needs such as food, water, and shelter. A priority shortly
594 after is to spur agricultural production for growers' own food production, resilience, and sales. For RTB
595 crops, attention should focus on seed verification and providing clean seed to growers, including growers
596 displaced from neighboring regions or countries. For example, if humanitarian agencies purchase ware
597 potato to distribute as seed, this introduces the risk of pests and disease to the people they are trying to
598 benefit. Clean or certified seed is a costly investment, and currently, the capacity to distribute clean seed

across the country does not exist in Cameroon and Ethiopia. These risk analyses are a first step toward

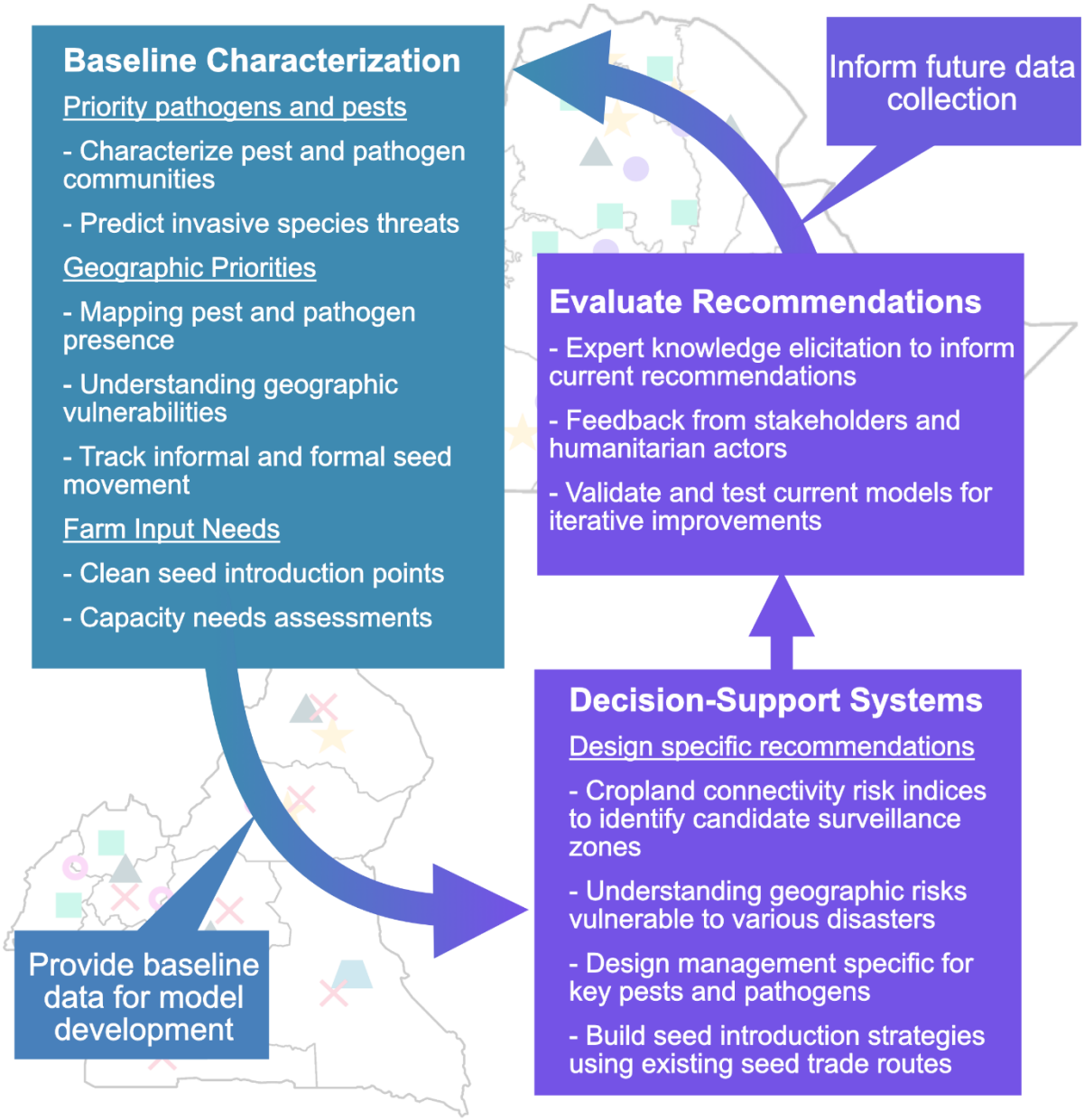

Figure 6. A framework for development and ongoing improvement of a national plant health risk analysis, to assist in addressing crop health in humanitarian settings. This approach can help to safeguard food production for vulnerable communities prior to and following disasters, and help to streamline and optimize humanitarian assistance.

creating a national plant health risk analysis to identify priorities for aid, to optimize deployment of clean

seed that is currently available. For example, providing clean seed to growers in regions with common

seedborne pathogens and pests may be a candidate priority. Locations that have informal trade with many other regions are also a candidate priority, to reduce dispersal of pathogens and pests. Following a crisis, understanding the informal trade of seed as well as trade in food can help identify management intervention priorities.

In seed degeneration, pathogens and pests accumulate over cycles of seed saving by growers, leading to a progressive reduction in crop yield and quality (Navarrete et al., 2022; Thomas-Sharma et al., 2017). This problem is exacerbated in Cameroon and Ethiopia since significant numbers of refugees and displaced people have been integrated into local communities, adding a further challenge to accessing clean seed and food. There is often a lack of networks for accessing formal services and resources (ECPHAO, 2023; TGHAT, 2022). In Cameroon, for example, 90% of the agricultural market is informal (OCHA, 2023a). The informal seed trade network reported in expert knowledge elicitation indicates the risk of pathogen and pest spread through trade hubs (**Figures 4 and 5**), both within each country and with neighboring countries (Andersen Onofre et al., 2019; Delaquis et al., 2018; Nduwimana et al., 2022).

Risk assessment of potential seed sources, initial seed testing (when stocks are obtained), maintenance of seed quality at multiple stages of the delivery chain, and charting of specific sources of original clean planting materials are all essential next steps for humanitarian programs before and during on-the-ground interventions. Geographic pathogen and pest risk assessments (Andersen Onofre et al., 2021; Thomas-Sharma et al., 2017) can be an important component of strategies to target resources in countries affected by natural or human-driven disasters (Etherton et al., 2024b). Cropland connectivity analysis, or more general habitat connectivity analysis, could be used before, during, and after crises to identify candidate priority locations where preventative or mitigation efforts are likely to have a greater impact on slowing pathogen or pest spread (Xing et al., 2020). Maps of connectivity (CCRI) show surrounding regions that may also play an important role in epidemics, which may be priorities for

625 providing clean seed to fleeing and displaced populations who are planting in new locations, or for seed
626 testing to mitigate disease establishment.

627 In Cameroon, a national plant health risk analysis can likewise support communities recovering
628 from disasters that have made planting material scarce. Experts also pointed out that, with multiple
629 conflicts and crises and repeated natural disasters (such as droughts, floods, or landslides), both in
630 Cameroon and neighboring countries (Nigeria and the Central African Republic), populations tend to move
631 to neighboring countries or villages, return to their villages during periods of calm or harvests, and flee
632 again as soon as conflict intensity increases. ECPHAO (2023) reports that the ongoing separatist conflict in
633 the Northwest and Southwest regions has displaced 80,000 Cameroonians to neighboring villages in
634 Nigeria, while violence in the Central African Republic and conflict with Boko Haram in northern Nigeria
635 led to a massive influx of over 491,000 refugees into neighboring Cameroonian villages (ECPHAO, 2023).
636 Inter-community conflicts, linked to the scarcity of water and other resources, broke out in 2021 between
637 populations in the Far North, resulting in the displacement of over 70,000 people, 35,000 of whom sought
638 refuge in Chad (ECPHAO, 2023; FAO, 2021b). Growers fleeing with their goods (including fresh planting
639 material) have the potential to introduce seedborne pathogens and pests into new regions, which is
640 particularly important if they are new pathogen or pest species or key subpopulations (such as new
641 pathogen mating types). Introductions may also be particularly important in regions that have high
642 cropland connectivity, such as some locations in Chad. The Boko Haram conflict in northeast Nigeria
643 caused 138,000 refugees to flee to Far North Cameroon (ECPHAO, 2023). Foyou et al. (2018) also reported
644 that in Cameroon, the crisis caused by Boko Haram in the Far North region increased the vulnerability of
645 the agricultural and economic system and caused the internal and external displacement of millions of
646 people.

647 In Ethiopia, flooding in central Amhara (**Figure 1**) can occur along with conflicts such as the Tigray
648 Civil conflict affecting the Amhara-Tigray border. With ongoing improvement to the maps of the pest and

649 pathogen communities present in Amhara (**Figure 3**), when a flooding disaster strikes, humanitarian aid
650 could prioritize management of diseases like potato early blight, bacterial wilt, and late blight, which are
651 exacerbated during floods (Guchi, 2015; Meno et al., 2020). When growers flee from disasters like the
652 Tigray Civil conflict, they may take seed with them, unknowingly bringing these pest and pathogen
653 communities with them. When locations are understood to be particularly important in terms of epidemic
654 connectivity, as suggested in the baseline analysis for Oromia (**Figure 2**), prioritizing resources like clean or
655 good quality seed for displaced people fleeing to such regions is a good strategy. For example, Etherton et
656 al. (2024a) concluded that the risk of reintroducing the *Ralstonia solanacearum* species complex (RSSC) to
657 Ethiopia from Kenya through trade was an important consideration, as was the risk of spreading the RSSC
658 from Ethiopia to neighboring countries. In Ethiopia, IOM (2023) reported that ethnic and/or territorial
659 conflicts and drought had a huge impact on agricultural production, causing the internal displacement of
660 over 4.8 million people in 2022 and 2023. An assessment of agricultural performance conducted in 2022
661 reported that about 1.2 million households in four regional states of Ethiopia needed emergency seed and
662 other input support to resume agricultural activity in the 2023 cropping seasons (RBA, 2022).

663 Knowledgeable farmers have some options for protecting their crop health even when seed
664 systems lack formal seed testing. Farm-to-farm transfer of planting material usually occurs at the village
665 level, where recipient farmers could have first-hand knowledge of the health of their neighbors' planting
666 material (Sperling & Almekinders, 2023; Sperling & McGuire, 2010). In some cases, farmers may even
667 inspect the fields themselves before accepting seed. Planting material transactions also routinely take
668 place in local and regional markets – for potato and increasingly for other RTB crops. Seed is sometimes
669 purchased from traders who may source from geographically distant or agro-ecologically diverse farms
670 (Sperling et al., 2020). As a result, farmers typically rely on information provided by intermediaries, like
671 neighboring farmers, local market traders, and itinerant traders selling across expansive regions. Some of
672 these sellers do have their own criteria for screening seed quality, like visual cleanliness of the planting

material or its vigor, or its freshness of color. However, for many, screening for disease, especially disease with more cryptic symptoms, is a formidable challenge. Farmers, traders, and humanitarian aid groups should be trained in selection for good-quality seed, combined with a strategy of regular seed replacement, which could prove beneficial in areas with no formal seed system. This should be the first line of defense for safeguarding seed systems: education and training.

4.4 Conclusions

Integrating the best available national plant health risk analysis in routine disaster risk reduction activities in countries experiencing multiple disasters can provide a baseline for rapid synthesis and 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.

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