Pathogen and pest risks to vegetatively propagated crops in humanitarian contexts: geographic priorities for Cameroon and Ethiopia

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Abstract

Cameroon and Ethiopia face complex humanitarian crises that disrupt the production of key food security crops like banana and plantain, cassava, potato, and sweetpotato. These vegetatively propagated crops are prone to the buildup of pests and diseases causing seed degeneration. In this study, we address seed degeneration in the context of natural and human-driven crises, to provide insights that can guide the decisions of humanitarian groups to reduce seed degeneration. We identified locations in Cameroon and Ethiopia that are likely to be particularly important for pathogen and pest spread in cropland network analyses. We analyzed cropland networks in each country to develop a map of locations that are candidate priorities for disease and pest management and surveillance. For example, locations in central and western Oromia, Ethiopia, are likely important for potato pathogen and pest spread given the locations' roles in the cropland network. Next, we used expert knowledge elicitation to characterize crop health risk in these systems. For example, experts reported with high consensus that there are formal and informal imports of cassava from Gabon to Cameroon, which pose a risk to cassava production in Cameroon through seedborne pathogens. These results can inform regional and national surveillance and management strategies and provide a baseline for more in-depth studies in Cameroon and Ethiopia. The results can also 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.

1.0 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 $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 materials that include 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 seed, leading to subsequent infestation and infection (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 trade (Scott, 2021; Sperling & Almekinders, 2023; Sperling et al., 2020). Informal trade of RTB crops is the primary method for growers in low-income countries to acquire seed, providing little or no phytosanitary control (Sperling & McGuire, 2010). Formal seed trade can provide certified disease-free seed, but often at a high price, which can deter growers even when formal seed systems are available. As groups such as FAO and USAID emphasize improved seed aid, there is a knowledge gap for effective improvement for RTB crops. In this study, we focus on seed systems in Cameroon and Ethiopia, two countries which rely heavily on informal seed trade and on RTB crops for both income generation and food security (Hirpa et al., 2010; OCHA, 2023a). Prioritizing the resilience of RTB seed systems in these two countries can help to meet the challenges of natural and human-driven

88 disasters. Disasters can challenge RTB crop health if sufficient attention is not given to managing pest and
89 disease risk in humanitarian responses.

90 **1.2 Ongoing disasters and humanitarian needs in Cameroon and Ethiopia**

91 Disaster plant pathology (Etherton *et al.,* in review) addresses the key drivers of plant disease
92 associated with disasters, and the solutions available during these crises. Cameroon and Ethiopia face a
93 wide range of humanitarian challenges, prompting the analysis of these country's seed systems in the
94 context of disaster plant pathology. In Cameroon, humanitarian crises include natural disasters that affect
95 nearly every part of the country, such as flooding, deforestation, desertification/droughts, and landslides
96 (Bang, 2021; Bang & Balgah, 2022) **(Figure 1, I)**. Additionally, there are human-induced challenges
97 including armed conflicts like the Boko Haram insurgency in the Far North region, the separatist conflict in
98 the Northwest and Southwest regions, societal challenges related to the influx of refugees from the
99 Central African Republic in the East, Adamawa and North regions, and political instability across the nation
100 (Bang & Balgah, 2022; Mbah et al., 2023). The agricultural communities in these areas are affected by
101 these compounding crises, diminishing already limited resources. Growers are abandoning their fields due
102 to these natural and human-induced crises, with the risk of food shortages affecting their families (FAO,
103 2021a, 2021b; OCHA, 2023a). Cameroon hosts more than 450,000 refugees and asylum seekers every
104 year, and the demand for humanitarian aid continues to grow (Macrotrends, 2023; OCHA, 2022).
105 Humanitarian access, though, remains a major challenge due to administrative obstacles, insecurity
106 instilled by armed groups, and infrastructure damage (ECPHAO, 2023).

107 Humanitarian crises in Ethiopia are often associated with drought, armed conflict, pest outbreaks,
108 and political instability, of which drought is a main factor reducing agricultural production and increasing
109 malnutrition among the affected communities (Alasow et al., 2023; CDP, 2023; Wubaye et al., 2023)
110 **(Figure 1, II)**. The frequency of droughts affecting cropland in Ethiopia has nearly doubled in the last 50

years (Alasow et al., 2023) and the severe drought that began in 2020 has continued into 2023, with Ethiopia enduring five failed rainy seasons (Alasow et al., 2023; CDP, 2023; Wubaye et al., 2023). In addition to drought, Ethiopia has experienced several armed conflicts, including the Tigray civil conflict, and disputes between the Ethiopian military and the militias in Amhara, creating a dire situation for more than five million people across these regions (CDP, 2023). The compounded effects of climate shocks, armed conflicts, and related displacement, continue to create unprecedented humanitarian needs, with more than 20 million people requiring food assistance in the year 2023 (OCHA, 2023b). In addition to a loss of assets and planting material, a significant proportion of growers affected due to multiple disasters cannot save seed, causing a staggering demand for seed supply as part of the emergency response. The

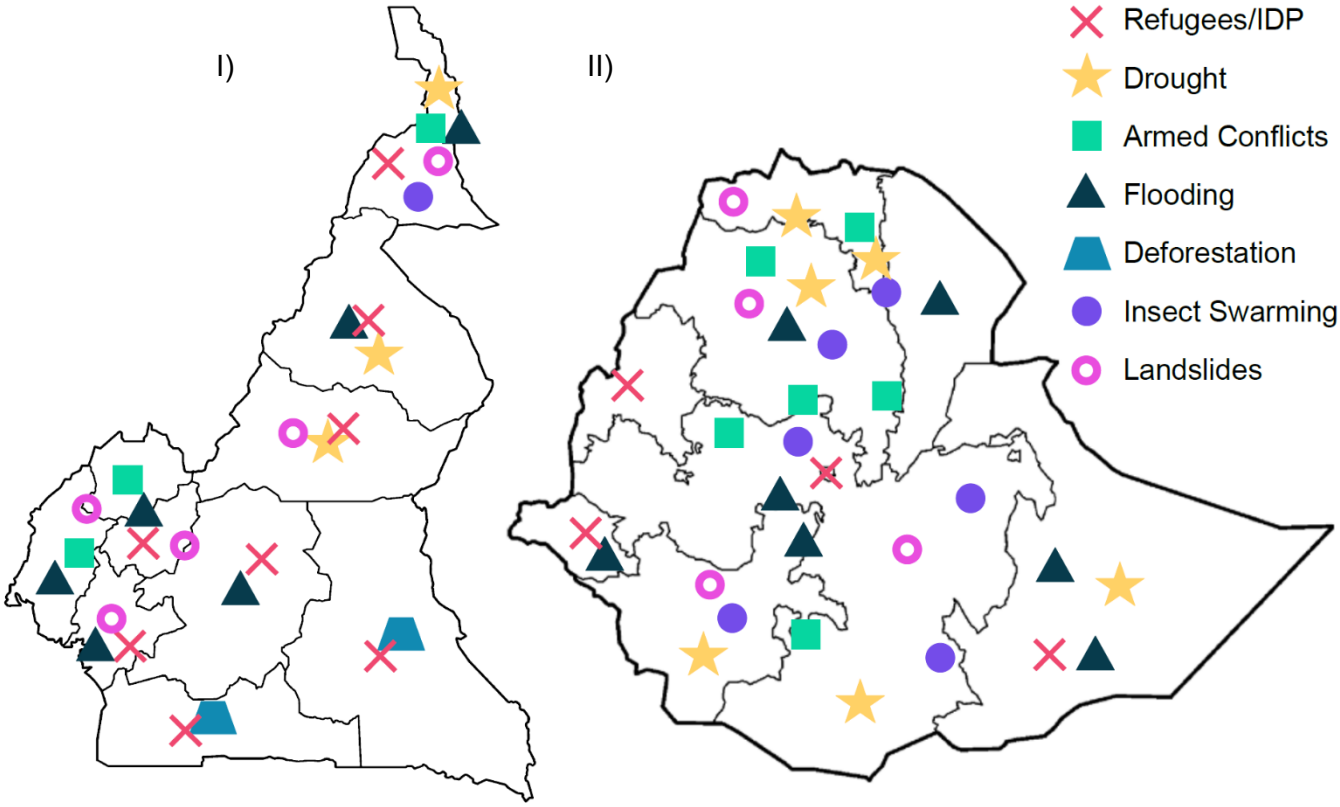

Figure 1. Maps of Cameroon (I) and Ethiopia (II) with representative types of disaster and humanitarian issues in the regions of the country. Each icon represents a type of disaster or major conflict affecting agricultural production, where red 'X's represent refugees issues and/or internally displaced people (IDP). These icons are placed approximately and do not reflect exact location or every reported disaster. Data adapted from Bang and Balgah (2022), IOM (2023), and Raleigh et al. (2010)

affected population may also need various types of emergency recovery support including fertilizer, farm tools, and cash to resume agricultural activities.

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 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 natural disasters occur, the relevance of agricultural interventions depends on several factors: the affected population, displacement, seasonal timing, available resources, and security considerations (e.g., whether growers can safely engage in cultivation amidst ongoing stressors). A key priority is ensuring the availability of disease-free seed, through market interventions or direct distribution, and this should be, at a minimum, quality seed of known low pathogen and pest levels (Nduwimana et al., 2022; Sperling et al., 2022).

There is often limited Information about the range of pathogens and pests that are a concern for plant health, and their potential spread through planting materials and other means, even when studies 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 on 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 that have needed resistance genes, when 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 is important. However, often the source and health status of potential seed are unknown and seed regulatory systems may not function to provide assurance of seed quality. This highlights the importance of rapid risk assessment tools to identify regions likely to be important in pathogen and pest spread, target economically consequential pests and pathogens, and assess the role of informal trade in the spread of pathogens during human population displacements (Carvajal-Yepes et al., 2019; Thomas-Sharma et al., 2017; Xing et al., 2020). This information is important both for identifying risks for emergency seed aid and for longer-term development strategies.

In this study, we use two complementary approaches to 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 aid allocation and mitigate the disease and pest threats to agricultural communities. Cropland connectivity analysis provides a map 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 (Margosian et al., 2009; Xing et al., 2020). 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 et al., 2019; Andersen Onofre et al., 2021; Buddenhagen et al., 2017; Buddenhagen et al., 2022). The second approach is expert knowledge elicitation, which can provide a summary of crop experts' knowledge about the current RTB seed systems and identify gaps in domain knowledge (Andersen Onofre et al., 2021; Thomas-Sharma et al., 2017). Cropland connectivity analysis and expert knowledge elicitation can be used for rapid risk assessments and to provide 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 and formal seed trade. We expand these analyses for Cameroon to include two more major food security crops: banana and plantain, and cassava. We brought together a group of experts in both Cameroon and Ethiopia to collect data regarding the RTB seed systems currently being used. We contextualize these analyses in the humanitarian risk scenarios in Cameroon and Ethiopia that result from armed conflicts and extreme weather events, to translate the results as input for decision-making by humanitarian organizations, donors, and national programs to potentially shape regulatory policy as well as to guide specific practical action on the ground.

2.0 Methods

2.1 Cropland connectivity for pathogens and pests

We used a cropland connectivity analysis to map locations likely to be important in outbreaks of pathogens and pests of banana and plantain (or simply banana, henceforth), cassava, potato and sweetpotato. Crop-specific harvested area across Sub-Saharan Africa (International Food Policy Research, 2020) for banana, cassava, potato and sweetpotato was used to evaluate a cropland connectivity risk index (CCRI) as described by Xing et al. (2020), with code available in the geohabnet package in R (Plex Sulá *et al.,* in review). The CCRI was evaluated separately for each crop, based on networks of potential spread among hosts for crop-specific pathogens or pests. The CCRI was defined as the weighted sum of four network metrics, to capture a range of potential roles a location may have during an epidemic or pest invasion: 1/2 the node betweenness centrality to account for a location's potential role as a bridge for spread between regions, 1/6 node strength to represent a location's potential importance as a hub for

spread, 1/6 the sum of a node's nearest neighbors' node degrees to account for the role of neighbors' neighbors, and 1/6 eigenvector centrality to account for both quantity and quality of links in an invasion network.

Cameroon and Ethiopia were the focus countries in these analyses. The cropland within each country and in the immediate surrounding countries (±0.5° latitude and longitude) were included. Locations with harvested areas greater than zero were retained as nodes, and a gravity model was used to evaluate the relative likelihood of dispersal between each pair of nodes (Jongejans et al., 2015). The dispersal kernel was based on an inverse power law model, $d_{ij}^{-\beta}$ in some components of a sensitivity analysis, and in other components of the sensitivity analysis based on a negative exponential model, $e^{-\gamma d_{ij}}$, where d_{ij} represents the distance between two nodes i and j, and the β and γ parameters indicate the likelihood of pathogen movement across that distance (Andersen Onofre et al., 2021; Xing et al., 2020). For example, 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 $\gamma = 2$. A range of β and γ values were evaluated in the sensitivity analysis, as described in Xing et al. (2020), and the mean results across these analyses are reported to provide a general connectivity measure for each location. We generated maps of the CCRI using R (version 4.3.2) for each crop for both Cameroon and Ethiopia using the raster package (version 3.5-15) (Hijmans, 2023). Higher CCRI scores indicate locations that are more likely to play an important role in an epidemic or invasion based on host availability and pathogen or pest dispersal, according to their geographic proximity and likely role in an epidemic or invasion network.

210 ## 2.2 Expert knowledge elicitation

211 We developed a survey for use in expert knowledge elicitation for Cameroon and Ethiopia to
212 capture the knowledge of RTB experts currently working in the field. Considering the limited database on
213 seed systems in humanitarian situations, the goal was to build an interactive interface specifically
214 designed for expert knowledge elicitation, in the broader context of the Rapid Risk assessment for
215 Mitigation (R2M) toolbox (garrettlab.com/r2m/). Expert knowledge elicitation can be used to assess the
216 risk of pest and pathogen spread through seed in humanitarian areas, and to help countries formulate
217 rational management strategies against invasive crop pests and pathogens.

218 The first stage of survey development was to review the content of the country-specific versions
219 of the survey with the organizing team to make sure it was appropriately matched to the situation in each
220 country. The surveys focused on RTB pathogens and pests causing high yield loss, with potentially
221 important impacts on vulnerable human populations in humanitarian situations. Expert knowledge
222 elicitation was developed to capture expert knowledge in Cameroon, in four surveys covering banana,
223 cassava, potato and sweetpotato. Similarly, two surveys were designed for experts in Ethiopia, focusing
224 on potato and sweetpotato. Surveys were deployed using Google Forms (Vasantha Raju & Harinarayana,
225 2016). Experts from Cameroon and Ethiopia participated in a one-day workshop in November 2022 in
226 Yaoundé, Cameroon, and in March 2023 in Addis Ababa, Ethiopia. In Cameroon, we recruited 18 experts
227 for cassava, 13 for potato, 10 for banana and 7 for sweetpotato. In Ethiopia, we recruited 20 experts for
228 potato, and 9 for sweetpotato. Experts known to have experience with these crops were selected from
229 governmental organizations, the private sector, NGOs and CGIAR centers (IITA, CIP, and Alliance
230 Biodiversity-CIAT). Experts were invited to complete the surveys individually, according to their crop
231 expertise. In each survey, experts were asked to identify the major pests and diseases, characterize the
232 crop-specific seed system, and identify the trade routes for seeds and harvested products within the
233 country and with neighbouring countries. After experts completed responses individually, experts were

234 then asked to discuss their choices in small groups and come to a consensus, similarly to the Sheffield
235 protocol of expert knowledge elicitation (Gosling, 2018; O'Hagan, 2019).

236 Answers from experts were compiled and organized by administrative zone boundaries in each
237 country. For Cameroon, the regions are Far North, North, Adamawa, East, Centre, South, Littoral, West,
238 Northwest, and Southwest. For Ethiopia, the regional states are Tigray, Afar, Amhara, Benishangul-
239 Gumuz, Somali, Oromia, Gambela, Southwestern, Southern Nations, Addis Ababa, Dire Dawa and Harari.
240 An initial list of key pathogens and pests was drawn from previous studies carried out in both countries,
241 and based on preliminary discussions with the organizing team. The pathogens and pests identified by
242 experts to be present by administrative zones were compiled, and represented as "major pest and
243 pathogen communities" using the R packages ggplot2 (version 3.3.6) (Wickham, 2016) and leaflet (version
244 2.1.1) (Graul & Graul, 2016). Pathogen and pest communities reported by experts as present in a region
245 were visualized in mapped pie charts. For both countries, pest and pathogen community maps were
246 created for potato and sweetpotato, and for Cameroon also for cassava and banana. Note that a caveat
247 for comparison of locations is that locations with less crop production tend to have less attention by
248 experts, so lower expert experience in a region in a sense represents 'lower sampling effort'; that is,
249 regions and regional states where experts have less experience will tend to have lower numbers of
250 pathogen and pest species reported.

251 ## 2.3 Within-country informal seed trade

252 Experts were asked about the informal seed trade of potato, sweetpotato, cassava, and banana
253 between regions of a country. For each potential link between a pair of regions, the link weight was the
254 proportion of experts who agreed that there was informal trade between that pair. This proportion was
255 used as a proxy for the level of informal seed trade between a pair of regions. The node strength, or the
256 sum of link weights, of informal seed trade was then calculated for each region using the igraph R package

(version 1.5.0) (Csárdi et al., 2023). These estimates of informal trade were compiled for each crop in both countries and represented as networks using the ggraph R package (version 2.1.0) (Pedersen, 2022). These informal seed trade networks between regions were then plotted on a map of each country with political administrative boundaries, using the rgeoboundaries R package (version 1.2.9000) (Dicko, 2023).

2.4 Formal and informal trade in neighboring countries

Experts were asked about the informal trade of potato, sweetpotato, cassava and banana seed with neighboring countries. Experts individually indicated which countries they thought imported seed from and exported seeds to Cameroon or Ethiopia for each crop. The proportion of experts who thought trade occurred between two countries was used as an “international trade rating”. For example, if 9 of the 12 experts reported that informal exports of potato seed occur from Cameroon to Gabon, then this directed link would have a weight of 0.75, indicating higher relative confidence in the occurrence of trade. These ratings of informal imports and exports were collected and averaged for each crop-country combination and represented as networks using the ggraph R package (version 2.1.0) (Pedersen, 2022). Similarly, FAO import and export data were analyzed as formal trade networks between Cameroon, Ethiopia, and their respective neighboring countries (FAOSTAT, 2021). Products manufactured by roasting or sterilization were excluded in this trade data. FAO trade data were assembled for each crop, where the trade volume (in metric tons) between each pair of countries was averaged across 2006 to 2020 (FAOSTAT, 2021). For simpler visual comparison with the levels of informal trade, the averaged formal trade volume for each crop was rescaled between 0 and 1 to provide a “formal trade ratio,” the proportion of formal trade occurring relative to the reported informal trade occurring between Ethiopia, Cameroon, and their respective neighboring countries. For example, if the maximum formal trade volume of potato for Ethiopia was with Kenya, and was approximately 12 tons, then the trade volume for each Ethiopian potato trading partner country was divided by 12 tons to rescale the volume.

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 general dispersal models. We evaluated cropland connectivity for potato and sweetpotato in Cameroon and Ethiopia, and also for banana and cassava in Cameroon.

In Cameroon, our analysis of crop landscape connectivity indicated that, for banana pathogens and pests, locations in the Southwest, West, Northwest, Centre, South, East, and Adamawa regions are likely most important to the risk of establishment and spread, based on host availability **(Figure 2, I)**. For cassava, many locations in the regions of Cameroon, except in the Southwest region, are at risk of establishment and spread of pathogens and pests given cassava cropland connectivity within country and their proximity to highly connected large cassava croplands in neighbouring countries like Nigeria and Chad **(Figure 2, I).** For potato, locations in West, Nothwest, and Adamawa regions are the most exposed to the risk of establishment and spread of pathogens and pests **(Figure 2, I**). These high-risk potato cropping areas are fairly small, reflecting the limited extent of potato production across Cameroon and their geographic isolation with more extensive potato production in neighbouring countries. For sweetpotato, locations in West, Nothwest, Adamawa, North and Far-Noth regions are likely the most important to the risk of establishment and spread of pathogens and pests **(Figure 2, I),** 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 Southern Nations, Nationalities and Peoples (SNNP), with the highest CCRI scores occurring in the SNNP and central Amhara

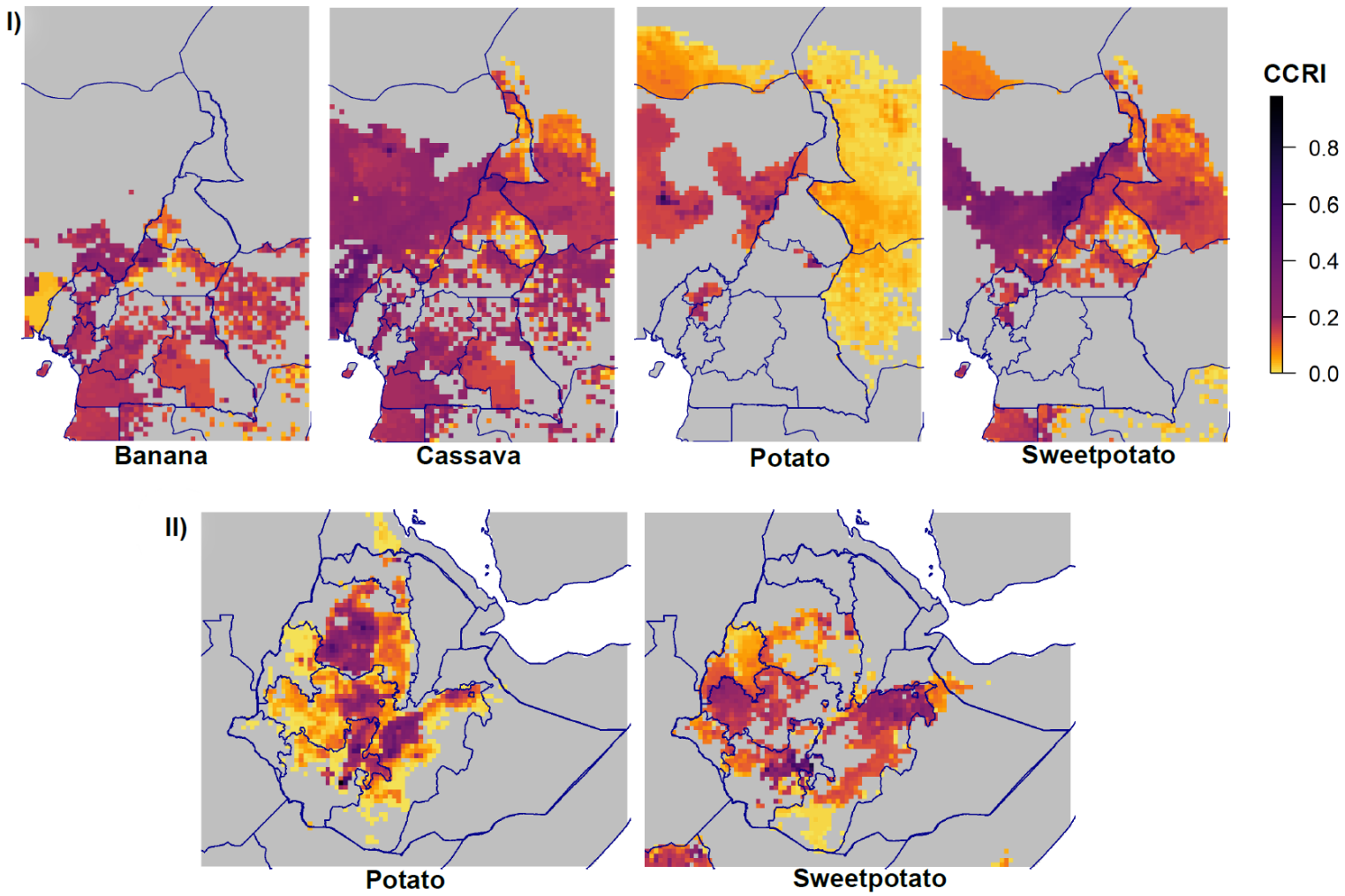

Figure 2. Maps of cropland connectivity risk indices for I) banana, cassava, potato, and sweetpotato in Cameroon and II) potato and sweetpotato in Ethiopia. The cropland connectivity risk index is based on networks of potential spread across a landscape of crop hosts; locations with higher cropland connectivity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

regions **(Figure 2, II)**. For Ethiopian sweetpotato, key locations include western Oromia and Benishangul-Gumuz, the border between SNNP and Sidama, and eastern Oromia including Harari and Dire Dawa **(Figure 2, II)**. The highest CCRI scores for Ethiopian sweetpotato were on the border between Sidama and the SNNP. Neighbouring countries were not strongly connected to Ethiopia in potato and sweetpotato cropland networks, as the reported harvested seed and production in neighbouring countries were relatively low **(Figure 2, II)**.

310 3.2 Expert knowledge elicitation: Pathogen and pest communities

311 For banana in Cameroon, the southern expanse was reported to have the highest major pathogen
312 and pest communities, with the South zone having a community of at least eight major pests and
313 pathogens **(Figure 3, I).** Anthracnose (caused by *Colletotrichum musae*) was reported present in every
314 region across Cameroon except the North and Far North; burrowing nematodes and yellow sigatoka were
315 reported present in every region except the North, Far North and Adamawa. Banana seed degeneration
316 was reported to be associated with the burrowing nematode, BBTV, banana weevil, anthracnose (caused
317 by *Colletotrichum musae*), and rhizome soft rot (caused by *Pectobacterium*).

318 For cassava, the East and Centre regions were reported to have the highest major pathogen and
319 pest communities, with the East, Centre, and South regions reported to have the presence of all 13
320 pathogens which were included in the expert knowledge elicitation survey **(Figure 3, I).** Cassava green
321 mite, cassava root rot, cassava mosaic disease, cassava mealybugs and cassava whitefly were reported as
322 present in every region across Cameroon. Cassava seed degeneration was reported to be associated with
323 CMV, cassava root rot (caused by *Fusarium* spp.), cassava anthracnose disease, ACMV, *Colletotrichum* spp.,
324 and cassava whitefly.

325 For potato, the western border was reported by experts to have the highest major pathogen and
326 pest communities, with the Northwest and Southwest zones having pathogen and pest communities of at
327 least 8 pathogens **(Figure 3, I)**. Early blight (caused by *Alternaria solani*), PVY, potato aphids and Fusarium
328 dry rot were reported to be present in seven of the ten regions across Cameroon, having the highest
329 reported presence by experts. The smallest major pathogen and pest communities were reported for
330 potato producers in Cameroon. Potato seed degeneration was reported to be associated with Fusarium
331 dry rot, late blight (caused by *Phytophthora infestans*), PVY, PLRV, and potato cyst nematodes.

For sweetpotato, the West region was reported to have the largest major pathogen and pest communities, with the South zone having the highest with six reported pathogens **(Figure 3, I).** The Northwest, West, Centre, and Littoral zones each had reported pathogen and pest communities of at least five pathogens. Early blight (caused by *A. solani*) and bacterial wilt (caused by *Ralstonia solanacearum*) were both reported as present in every region across Cameroon except the North and the Southwest. Sweetpotato seed degeneration was reported to be associated with sweetpotato viruses, Alternaria blight, Fusarium root rot, and bacterial wilt.

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

For Ethiopian sweetpotato, southern zones were reported by experts to have the highest pest and pathogen communities, with Sidama and the SNNP both reporting pathogen communities of at least 8 pathogens **(Figure 3, II)**. Alternaria blight and the sweetpotato weevil were reported in every region across Ethiopia, except for Somali and Addis Ababa, respectively. Experts also reported that some of these pathogens and pests caused seed degeneration in both crops in Ethiopia. Experts selected the key causes of seed degeneration as sweetpotato viruses, sweetpotato weevil, *Alternaria bataticola*, and sweetpotato aphids.

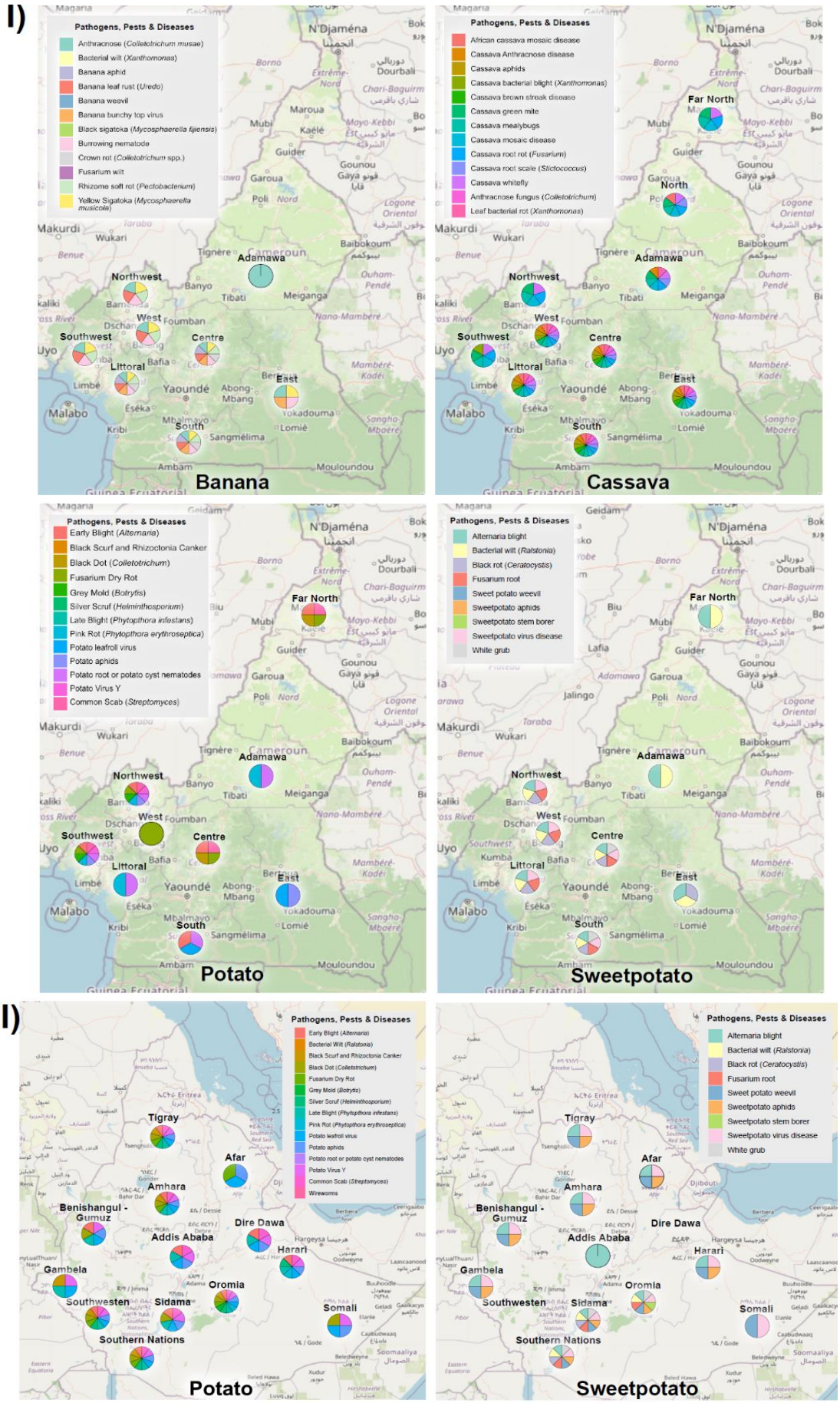

Figure 3. Maps of the reported presence of major diseases and pests in (I) Cameroon and (II) Ethiopia, from expert knowledge elicitation. Pie charts indicate whether a disease or pest was reported to be present in each region. Note that the absence of a report in the expert knowledge elicitation may be influenced by lower research efforts in regions with less crop production.

3.3 Expert knowledge elicitation: Within-country informal seed trade

We analyzed the network of seed exchange between regions in Cameroon and in Ethiopia, as reported by experts for potato and sweetpotato, to assess the risk of pathogen and pest spread through seed between regions. Experts reported high levels of exchange, suggesting a high risk for seedborne pathogen and pest spread between regions in both countries. For informal potato and sweetpotato seed trade in Cameroon, all the regions were reported to be interconnected. There was high seed trade strength reported in the West region for potato **(Figure 4, I)** and in the Centre and Littoral regions for sweetpotato **(Figure 4, I).** In Ethiopia, all the regions were also reported to be interconnected except the

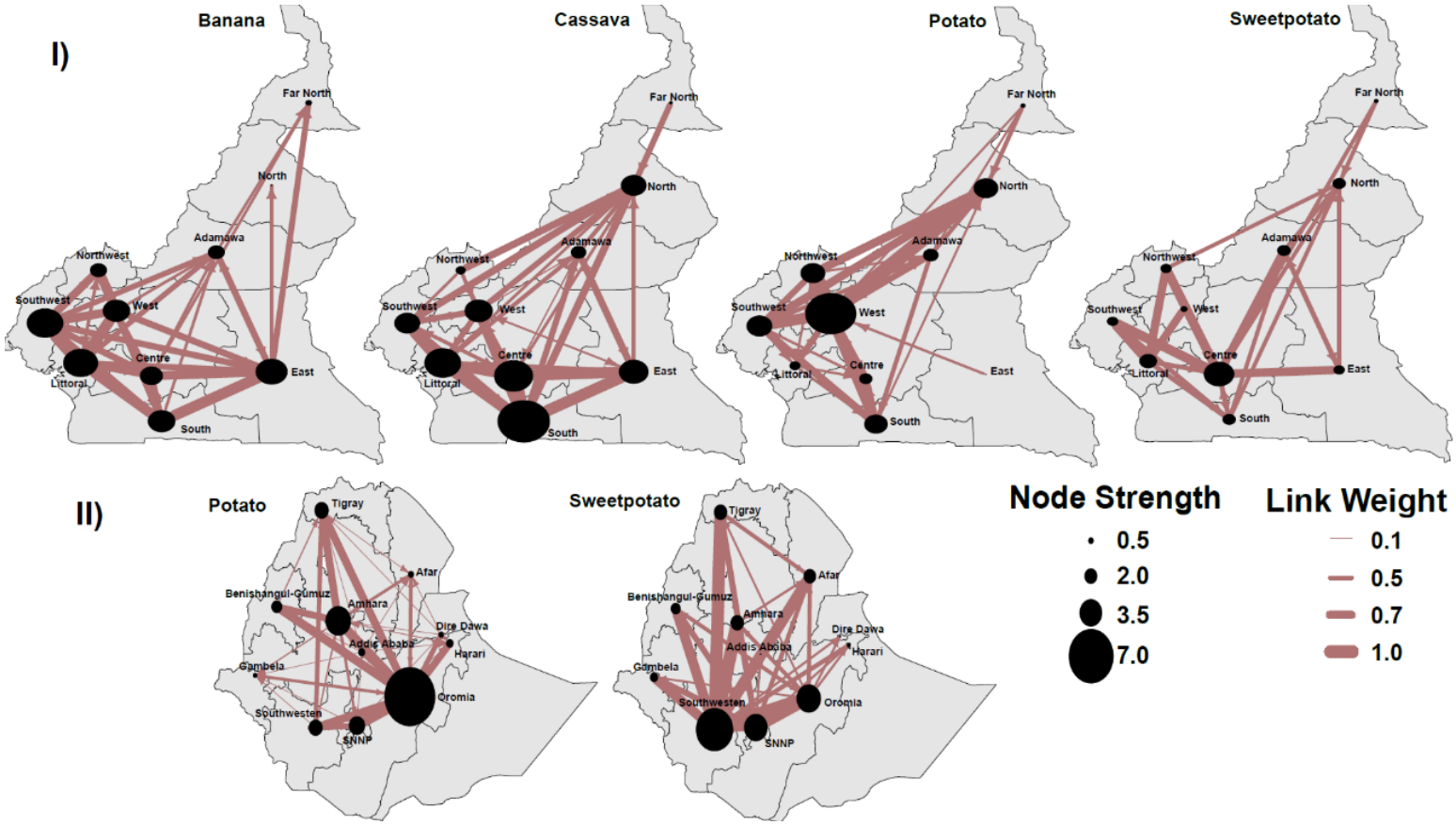

Figure 4. Informal seed trade networks between regions in I) Cameroon, and II) Ethiopia as reported in expert knowledge elicitation. Node size is proportional to node strength, or the sum of link weights. Link weights are the proportion of experts that agreed on the occurrence of informal trade between the linked regions.

Somali region. Seed trade strength was reported to be high in the Oromia and Amhara regions for potato **(Figure 4, II)** and in the Southwestern, SNNP, and Oromia regions for sweetpotato **(Figure 4, II).**

For banana and cassava in Cameroon, regions were reported to be well linked, with high regional informal seed trade strength for banana in the Southwest, Littoral, East, West and South regions **(Figure 4, I)** and for cassava in the South, Centre, Littoral, West and East regions **(Figure 4, I).** The experts also reported that, 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 seed and food. They also highlighted the vulnerable situation of many of these growers working in neighboring regions and countries.

3.4 Formal and informal trade with neighboring countries

We used expert knowledge elicitation and FAO trade data to characterize the informal and formal trade networks, respectively, linking Cameroon and Ethiopia with their respective neighboring countries. These networks were generated for potato and sweetpotato for both Cameroon and Ethiopia, and also for banana and cassava for Cameroon.

For informal potato trade in Cameroon, 38% of experts reported informal import of potato seed from Nigeria to Cameroon, and 30% reported informal export of potato seed from Cameroon to Gabon **(Figure 5, I)**. Informal export of potato seed to all neighboring countries from Cameroon was reported by at least one expert, and no experts reported that the Congo Republic was importing potato seed into Cameroon. For formal trade, exports and imports were reported between the Congo Republic, the Central African Republic and Gabon, with the highest trade volume average from Gabon imports.

For informal sweetpotato imports, 28% of experts reported that Gabon, Nigeria, and the Central African Republic imported sweetpotato seed to Cameroon, and 28% of experts reported that Cameroon exported sweetpotato seed to Gabon and the Central African Republic **(Figure 5, I)**. No informal imports to

Cameroon were reported to occur from Chad, Equatorial Guinea, the Congo Republic and Chad, and no informal exports were reported to occur to Equatorial Guinea. For the formal trade, the highest trade volume occurred from Gabon imports to Cameroon. Formal bidirectional trade occurred between Cameroon and Gabon, the Central African Republic, and the Congo Republic, and formal exports occurred to Equatorial Guinea. No informal or formal trade was reported to occur with Chad **(Figure 5, I)**.

For informal trade of banana seed in Cameroon, 40% of experts reported exports to Gabon, and 30% reported imports from Gabon and exports to Nigeria **(Figure 5, I)**. No informal imports were reported from Equatorial Guinea or Chad. The largest formal trade was exports to Chad, and secondly to Eritrea. No formal imports were reported from the Congo Republic, Chad, or Equatorial Guinea, and no formal exports occurred to the Central African Republic **(Figure 5, I)**.

For informal cassava trade in Cameroon, 72% of experts reported exports to Gabon, the highest reports across all surveys, and 50% reported imports from Nigeria **(Figure 5, II)**. Informal imports and exports were reported by experts for all neighboring countries except for informal imports from Chad **(Figure 5, I)**. For formal trade of cassava, FAO reported the highest trade volume occurring through Gabon imports. Formal imports were from Congo and Gabon, and formal exports were to the Central African Republic, Gabon, and the Congo Republic **(Figure 5, I)**.

For the informal Ethiopian potato seed trade, 30% of experts reported potato seed export to Djibouti, and 25% reported exports to Somalia and Sudan **(Figure 5, II)**. No experts reported informal imports from Somalia, Eritrea, and South Sudan. For formal trade, the highest trade volume was Ethiopian exports to Somalia. No formal imports or exports occurred between South Sudan and Eritrea, and no formal imports occurred from Sudan, Somalia, or Kenya.

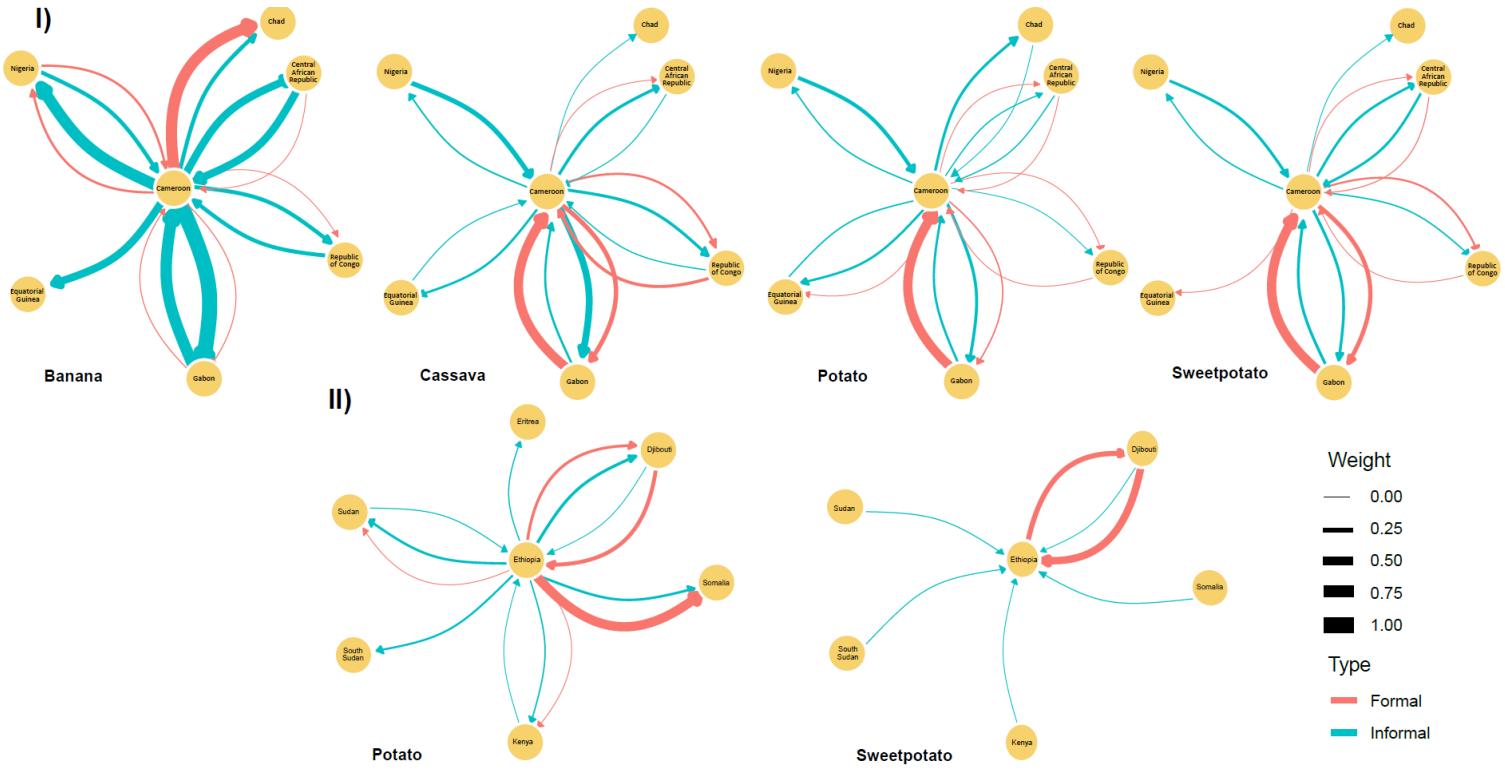

Figure 5. Formal and informal trade networks with neighboring countries for I) Cameroon and II) Ethiopia. Informal networks were reported in expert knowledge elicitation, and formal networks were based on FAO trade databases. Link width represents the relative confidence in the occurrence of trade (based on the proportion of experts reporting it), and color represents the trade type reported (formal or informal).

Informal trade of sweetpotato seed was reportedly rare from Ethiopia, where no exports of sweetpotato seed were reported **(Figure 5, II)**. Unlike exports, informal imports were reported from all neighboring countries except Eritrea, with only 11% of experts reporting these imports. Formal seed imports and exports were only reported to occur between Ethiopia and Djibouti.

4.0 Discussion

These analyses show the potential for crop pathogens and pests to spread quickly in Cameroon and Ethiopia, especially across the highly-connected regions identified here, potentially moving undetected through seed trade. Many actors may contribute to this unwanted movement: growers sharing seed, traders selling seed, and humanitarian groups and governments providing emergency or

415 developmental assistance. All of these actors need to be aware of the potential for pathogen and pest
416 spread, and to be equipped with tools to prevent unintentional spread, especially spread of new species
417 or problematic populations, such as pathogen populations with pesticide tolerance or the ability to
418 overcome crop resistance genes. Information about which geographic locations are likely to be particularly
419 important in pathogen and pest spread is an important first step in developing priorities and strategies for
420 investing limited resources to protect crop health. Seed testing and charting specific sources of clean
421 planting materials are the next line of defense and are essential for humanitarian interventions.

422 The spread of crop pathogens and pests is driven by a complex interplay of factors including
423 environmental conduciveness, the formal and informal movement of agricultural commodities, as well as
424 the density and connectivity of crops (Andersen Onofre et al., 2021; Buddenhagen et al., 2022; Garrett et
425 al., 2022; Margosian et al., 2009; Nduwimana et al., 2022; Xing et al., 2020). Complete information about
426 these factors is rarely available when decisions must be made about the emergency movement of food
427 and planting material in humanitarian crises, but the analyses we illustrate here can be performed
428 relatively quickly to provide baseline information about pathogen and pest risk. Geographic pathogen and
429 pest risk assessments (Andersen Onofre et al., 2021; Thomas-Sharma et al., 2017) are a key component of
430 agricultural resilience and food security in countries affected by natural or human-driven disasters
431 (Etherton et al. in review). These analyses help to identify the most vulnerable cropping regions and
432 regions likely important for disease establishment or spread. Analyses such as the ones reported here, and
433 the next generations of such analyses as tools are continually improved, should be routinely conducted in
434 crisis regions to help humanitarian organizations, donors, and governments assess the risks associated
435 with diseases and pests. This information is an important component of input to establish effective and
436 appropriate humanitarian responses that minimize risks, and ensure that affected populations have access
437 to sufficient nutritious food during and following crises. In this study, we assessed the key species and key
438 locations important for pathogen and pest spread in banana, cassava, potato, and sweetpotato for

439 Cameroon and potato and sweetpotato for Ethiopia. This information is intended as input to support
440 decision-making to form aid policies in response to crises and to prioritize considerations in humanitarian
441 implementation on the ground, and for those along the informal trade chains, such as growers, traders,
442 and producers.

443 The cropland connectivity analyses identified regions likely to be important for the establishment
444 and spread of crop-specific pathogens and pests, based on crop host availability. We found that locations
445 in the West, Northwest, and Adamawa regions of Cameroon presented the highest risk of pathogen and
446 pest spread for all banana, cassava, potato and sweetpotato crops, as did locations in the Oromia, Amhara
447 and SNNP regions of Ethiopia for potato and sweetpotato crops. For Cameroon, informal movement of
448 cassava and sweetpotato, should also be monitored, particularly to and from Nigeria, as Nigeria has high
449 CCRI scores for these crops as well and may be a refuge for immigrants during humanitarian crises. For
450 Ethiopia, neighboring countries had low CCRI scores, suggesting migrants from Ethiopia bringing their
451 seed pose a lower threat to the immediate surrounding cropping regions. Other examples of cropland
452 connectivity analyses are the identification of locations likely to be important for the spread of potato
453 pathogens and pests in Kenya and Ecuador (Buddenhagen et al., 2022) and the Republic of Georgia
454 (Andersen Onofre et al., 2021). Cropland connectivity analysis could be used before, during, and after
455 crises to identify candidate priority locations where investment efforts are likely to have a greater impact
456 on slowing pathogen or pest spread. Maps of connectivity (CCRI) show surrounding regions that may also
457 play an important role in epidemics, which may be priorities for providing clean seed to fleeing
458 populations who are planting in new locations, or for seed testing to mitigate disease establishment. For
459 example, in 2021 inter-community conflicts, linked to the scarcity of water and other resources, broke out
460 in Cameroon between populations in the Far North, resulting in the displacement of over 70,000 people,
461 35,000 of whom sought refuge in Chad. Growers fleeing with their goods (including cassava and
462 sweetpotato seed), based on cropland connectivity analyses, have the potential to introduce seedborne

463 diseases in cropland in Chad (ECPHAO, 2023; FAO, 2021b). Conversely, refugees fleeing into Cameroon
464 and Ethiopia may bring with them infected seed; for example, the Boko Haram conflict in northeast
465 Nigeria caused 138,000 refugees to flee to Far North Cameroon (ECPHAO, 2023).

466 The expert knowledge elicitation identified the major pathogens and pests reported by experts in
467 each region for both Cameroon and Ethiopia. We noted differences in the major pathogens and pests
468 between regions for the same crop, for example, experts reported few pests and pathogens in East
469 Cameroon for banana, potato, and sweetpotato, but every pest and pathogen evaluated for cassava.
470 Some pests and pathogens, for example, white grub in Cameroon, were only reported in Centre and South
471 Cameroon, and nowhere else in the country. The results of expert knowledge elicitation provide a basis
472 for rapid assessment in field studies. Expert knowledge elicitation has been used in other scenarios to
473 evaluate phytosanitary risk, for example by Andersen Onofre et al. (2021) to identify phytosanitary
474 strategies for protecting potato seed systems in the Republic of Georgia. Savary et al. (2019) used an
475 expert survey to estimate the yield losses due to pathogens and pests for five major food security crops.
476 This new study illustrates how expert knowledge elicitation can be used in crisis situations to identify the
477 main pathogens and pests that could have a major impact on food security and the incomes of vulnerable
478 populations. It can also be used to visualize the formal or informal trade network for seeds, harvested
479 products, and agricultural equipment in a country, as well as the displacement of populations during
480 crises, and analyze the potential risk of pathogen and pests spread between regions.

481 Several of the pests and pathogens identified in the expert knowledge elicitation contribute to
482 seed degeneration, which is a major concern in the cultivation of RTB crops in both countries. Pathogens
483 and pests accumulate over cycles of seed saving by growers, leading to a progressive reduction in crop
484 yield and quality (Navarrete et al., 2022; Thomas-Sharma et al., 2017). This problem is exacerbated in
485 Cameroon and Ethiopia since significant numbers of refugees and displaced people have been integrated
486 into local communities, adding a further challenge to accessing clean seed as well as food, itself. There is

487 often a lack of networks for accessing formal services and resources (ECPHAO, 2023; TGHAT, 2022). In
488 Cameroon, for example, 90% of the agricultural market is informal (OCHA, 2023a). Analysis of the informal
489 trade network reported in expert knowledge elicitation indicates that regions in both countries are well
490 connected, with a corresponding risk of pathogen and pest spread. Informal seed trade between regions
491 often leads to the introduction of new pathogens and pests to a region, which can reduce crop production
492 and the food security of vulnerable populations (Andersen Onofre et al., 2019; Delaquis et al., 2018;
493 Nduwimana et al., 2022). We identified key hubs for the potential spread of pathogens and pests in
494 Cameroon in the Southwest and Littoral (banana), the South, Centre, and Littoral (cassava), the Northwest
495 and West (potato), and the Centre and Littoral (sweetpotato). In Ethiopia, locations in the Oromia and
496 Amhara regions were potential key locations for potato, while locations in the Southwestern, Oromia and
497 SNNP regions were the potential key locations for pest and pathogen spread in sweetpotato.

498 The ongoing insecurity in the Northwest, Southwest, East, and Far North regions of Cameroon is
499 increasing displacement of people to other regions with their seed, harvested crops, and agricultural
500 equipment, often without knowledge of the basic phytosanitary rules that could be used during this
501 migration. These crises are likely to continue to increase the risk of pathogen and pest spread across
502 regions, leading to greater food insecurity and vulnerability for the country's population. In Ethiopia, IOM
503 (2023) reported that ethnic and/or territorial conflicts and drought had a huge impact on agricultural
504 production, causing the internal displacement of over 4.8 million people in 2022 and 2023. An assessment
505 of agricultural performance conducted during the main season of 2022 reported that about 1.2 million
506 households in four regional states of Ethiopia needed emergency seed and other input support to resume
507 agricultural activity in the 2023 cropping seasons (RBA, 2022). Foyou et al. (2018) also reported that in
508 Cameroon, the Boko Haram-induced crisis in the Far North region increased the vulnerability of the
509 agricultural and economic system of the region and caused the internal and external displacement of
510 millions of people.

Experts in this study reported that growers in both countries participate in informal trade in seed and harvested products with growers in neighboring countries. People living in border villages often have family members in neighboring countries and share the same local markets. Both informal and formal exchange of agricultural commodities increases the risk of seedborne pathogen and pest spread between Cameroon/Ethiopia and neighboring countries. For example, Etherton et al. (in review) concluded that the risk of reintroducing the *Ralstonia solanacearum* species complex (RSSC) to Ethiopia from Kenya through formal trade was an important consideration, as was the risk of spreading the RSSC from Ethiopia to other neighboring countries such as South Sudan, Sudan, Djibouti, and Somalia. Experts also pointed out that, with multiple conflicts and crises (since 2013) in Cameroon and neighboring countries (Nigeria and the Central African Republic), populations tend to move to neighboring countries during periods of intense conflict, return to their villages during periods of calm or harvests, and flee again as soon as conflict intensity increases. ECPHAO (2023) reports that the ongoing separatist conflict in the Northwest and Southwest regions has displaced 80,000 Cameroonians to neighboring villages in Nigeria, while violence in the Central African Republic and conflict with Boko Haram in northern Nigeria led to a massive influx of over 491,000 refugees into neighboring Cameroonian villages (ECPHAO, 2023).

The analyses here represent baselines for better understanding pathogen and pest risks in RTB systems in Cameroon and Ethiopia. When resources are available, there are many possibilities for improving on these analyses. For example, the cropland connectivity analyses represent a simplified view of the risk of spread by averaging across potential dispersal parameters, to represent many potential pathogens and pests. When dispersal is well-characterized for a particular pathogen or pest species, the cropland connectivity analysis can be implemented specifically for that species, and potentially expanded to a fuller habitat connectivity analysis, including other location traits such as environmental conduciveness to the species. The cropland connectivity analysis may also be improved as crop density maps improve in quality. Cropland connectivity analyses can also be a first step for scenario analyses for

535 regional pest and disease management, by providing an estimate of the potential epidemic or invasion
536 network for simulation experiments (Etherton et al., 2023; Garrett, 2021; Wiebe et al., 2018).

537 The results of expert knowledge elicitation can also be improved over time. Experts are limited by
538 potential biases and lack of knowledge. For example, experts may tend to have less knowledge about
539 locations where a particular crop is less commonly produced, so that there is less 'sampling effort' in
540 those locations in terms of expert knowledge. When resources are available for pathogen and pest
541 monitoring, new information can supplement summaries of expert knowledge. Expert knowledge
542 elicitation and habitat connectivity analysis are part of the developing R2M toolbox for rapid risk
543 assessment to support mitigation of plant pathogens and pests (garrettlab.com/r2m), designed for
544 continual improvement based on lessons learned in applications across countries and crop systems.
545 Related tools focusing on seed systems include the seed emergency response tool (Sperling et al., 2022),
546 the multi-stakeholder framework for RTB seed systems (Bentley et al., 2018), and other components of
547 the CGIAR tools4seedsystems toolbox (Andrade-Piedra et al., 2023). These tools can be used in
548 conjunction and incorporated into comprehensive risk management frameworks.

549 During times of crisis, first-order humanitarian aid should clearly be allocated to providing affected
550 people with basic needs such as food and water. A priority shortly after is to spur agricultural production
551 for growers' own food production and sale. For RTB crops, attention should focus on seed verification and
552 providing clean seed to growers, including growers migrating to neighboring regions or countries. Risk
553 analysis can be conducted prior to conflict, to create priority maps for aid. For example, providing clean
554 cassava seed to growers in Centre, East, and South Cameroon is a candidate priority, as these regions were
555 identified by experts as having many major cassava pathogens and pests. Based on cropland connectivity,
556 candidate priorities for clean potato seed provision in Ethiopia are locations in Amhara and central
557 Oromia. Following a crisis, understanding the informal and formal trade of seed can help to identify
558 management intervention points, for example, markets in Southwestern Ethiopia are a candidate priority

for surveying for sweetpotato diseases to stop the movement of seedborne pathogens, and similarly for potato markets in West Cameroon. 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 bodies to develop more formal seed testing programs nationally. It is through the collaboration of humanitarian groups, governmental programs, growers, and traders, 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

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, 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

Carvajal-Yepes, M., Cardwell, K., Nelson, A., Garrett, K. A., Giovani, B., Saunders, D., Kamoun, S., Legg, J., Verdier, V., & Lessel, J. (2019). A global surveillance system for crop diseases. *Science*, *364*(6447), 1237-1239.

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., Andersen, K. F., Minato, N., Cu, T. T. L., Karssenberg, M. E., Sok, S., Wyckhuys, K. A., Newby, J. C., Burra, D. D., & Srean, P. (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. A., Choudhury, R., Alcalá-Briseño, R., Xing, Y., Sulá, A. P., Carrillo, D., Wasielewski, J., Stelinski, L., Grogan, K., & Ballen, F. (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

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.

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,* 357-378. 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

Graul, C., & Graul, M. C. (2016). Package 'leafletR'. *Interactive Web-Maps Based on the Leaflet JavaScript Library. Available online: https://github. com/chgrl/leafletR (accessed on 1 April 2016)*.

Hijmans, R. J. (2023). raster: Geographic data analysis and modeling. R package version 3.6-21. https://rspatial.org/raster

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

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

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), E15124. https://doi.org/10.1016/j.heliyon.2023.e15124

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

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

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/10.1177/022343310378 91

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., & 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., 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*.

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