A nationwide assessment of major wheat diseases and pests in Pakistan

Aaron I. Plex Sulá[1,2,3], Muhammad Aqeel Sarwar[4], Sajid Ali[5], Naeela Qureshi[6], Kamran Saleem[7], Pawan Kumar Singh[6], Karen A. Garrett[1,2,3], Zunaira Afzal Naveed[8]

[1]Department of Plant Pathology, University of Florida, Gainesville, FL, USA

[2]Global Food Systems Institute, University of Florida, Gainesville, FL, USA

[3]Emerging Pathogens Institute, University of Florida, Gainesville, FL, USA

[4]Center for Advanced Studies in Agriculture and Food Security, University of Agriculture Faisalabad, Pakistan

[5]Department of Agriculture, Hazara University, Mansehra, Pakistan

[6]International Maize and Wheat Improvement Center (CIMMYT), Texcoco, México

[7]Nuclear Institute for Agriculture and Biology (NIAB), Faisalabad, Pakistan?

[8]Center of Agricultural Biochemistry and Biotechnology, University of Agriculture, Faisalabad, Pakistan

Aaron I. Plex Sulá and Muhammad Aqeel Sarwar made equivalent contributions

Corresponding authors: Zunaira Afzal Naveed (dr.zunaira@uaf.edu.pk) and Karen A. Garrett (karengarrett@ufl.edu)

Abstract

Wheat production in Pakistan faces persistent threats from diseases and pests. However, little geographic information is available for their local risks, economic impacts, and management distribution. We used expert knowledge elicitation to characterize the geographic burden and potential spread of key wheat pathogens and pests. Experts mapped yield losses for major stressors – leaf rust, stem rust, stripe rust, aphids, armyworm, loose smut, Fusarium head blight, and karnal bunt – at the district level. Network analysis traced seed and grain exchange routes and stakeholder interactions. Analysis of wheat cropland connectivity identified locations that are likely to play important roles in epidemics. Expert-estimated yield losses, summed across diseases and pests, ranged from 4% to 16%, with hotspots in Punjab and northern Sindh. Informal movement of wheat seed (70-75%) and grain (68-97%) is common within local trade networks, being key for managing the spread of seedborne pathogens. Stakeholder interaction networks indicate the likely roles of research institutes, extension

actors, and farmer organizations in the exchange of management information and plant material. Cropland connectivity analysis identified a north-south corridor of highly connected wheat landscapes, overlapping with pest hotspots and potentially facilitating pathogen proliferation. This study provides the first integrated assessment of wheat disease and pest pressure in Pakistan and serves as a baseline for improvement of geographically targeted disease surveillance and coordinated management interventions. These findings highlight critical control points in the biological and institutional networks, offering actionable insights for enhancing national plant health in wheat-based systems.

Introduction

Wheat (*Triticum aestivum*) is the most economically important staple crop in Pakistan, underpinning food security and the livelihood of over 160 million people (Pakistan Bureau of Statistics). In 2018, wheat production contributed ~24% to gross domestic product (~US$) and 37.4% of national workforce (Government of Pakistan, 2018). Cultivation of wheat in Pakistan spans over ~9.2 million hectares (or ~40% of the total cropped area), with an average yield of ~2.7 tonnes per hectare (Ali et al., 2017; Shaukat et al., 2023). Wheat productivity faces persistent biological and abiotic challenges, such as increased risks from climate change, limited agricultural innovation, and underdeveloped infrastructure (Ranaivoson et al., 2019; Siddig et al., 2020).

In recent decades, wheat production in Pakistan has suffered from recurring disease epidemics and pest outbreaks, contributing to significant yield and economic losses (Rattu et al., 2011). Among biological threats, rust diseases caused by *Puccinia* spp. are historically the most damaging, with yellow or stripe rust (*P. striiformis* f. sp. *tritici*) and leaf or brown rust (*P. triticina*) being the most prevalent across major wheat-producing areas (Ali et al., 2014; Hovmøller et al., 2010; Khan et al., 2020). Yellow rust, once confined to cooler high-altitude zones, has now expanded into warmer plains, exemplified by the devastating 2003–2004 epidemic on cultivar Inqilab-91, which affected 80% of the wheat-growing area (Fayyaz et al., 2017; Majeed et al., 2025). Leaf rust is particularly common in the wheat-rice and cotton-wheat belts and causes consistent annual yield losses. Stem rust (*P. graminis*) is globally significant but remains sporadic in Pakistan and is primarily observed in coastal Sindh. Other fungal diseases include powdery mildew, which has shown increasing incidence in northern Punjab since 2022, especially under humid conditions and zero tillage practices. Karnal bunt (*Tilletia indica*), though low in frequency, poses international trade risks due to its quarantine status (Aasma et al., 2019). Loose smut, spot blotch, and Fusarium head blight occur sporadically but can contribute to grain quality degradation (Rattu et al., 2011).

Insect pests such as aphids, especially *Schizaphis graminum*, and armyworms are additional major contributors to wheat yield losses. Aphids not only cause direct damage by sap-sucking but also transmit viruses like the cereal yellow dwarf virus (Wains et al., 2014). Other pests such as cereal leaf beetles and termites are considered minor but locally impactful. Recent unpublished surveys (2022–2025) indicate that national disease dynamics are influenced by weather, variety, and pathogen races. While rusts remain dominant, the emergence of powdery mildew and shifting pest distributions underscore the need for robust surveillance. Although abiotic stresses like terminal heat and drought significantly impact wheat production in Pakistan, this paper focuses on biological threats, which are comparatively under-monitored yet highly damaging.

In response to persistent biotic threats, Pakistan has implemented several measures to enhance national biosecurity and manage the spread of wheat diseases and pests. Under the Ministry of National Food Security and Research, the Department of Plant Protection (DPP) enforces phytosanitary regulations including Pest Risk Analyses (PRAs) for wheat imports, fumigation or heat treatment of high-risk consignments, and the issuance of Phytosanitary Certificates in line with IPPC standards (Government of Pakistan, 2023; IPPC, 2016). Recent actions have also addressed seedborne quarantine pathogens such as *T. indica* (Karnal bunt), with stricter import protocols and enhanced surveillance following regional outbreaks (Tribune, 2024).

Although several regional studies have provided important insights into specific diseases and pests (Bahri et al., 2011; Khan et al., 2019, 2021; Shafi et al., 2021; Awais et al., 2023), a nationwide, geographically resolved assessment of wheat health threats is lacking. In practice, passive surveillance conducted by agricultural officers or farmers is the primary source of pest and disease data, with occasionally targeted inspections by researchers. These methods are limited in scale and often fail to capture the full spatial patterns of pathogen and pest distributions. Rust surveillance is relatively advanced in Pakistan, supported by national initiatives and collaborations with global programs like the Borlaug Global Rust Initiative (BGRI). In addition, Pakistan engages with international partners such as CABI to support early warning systems, particularly for rusts and invasive pests (CABI, 2023). A surveillance system operating across non-rust diseases and pests remain underdeveloped, leading to delayed detection and limited response to emerging threats.

In resource-limited settings like Pakistan, nationwide pest and disease surveillance remains challenging due to financial and logistical constraints (Gustafson et al., 2013). This limits access to timely data needed for strategic decision-making. To address this constraint, expert knowledge elicitation (EKE) offers a structured, cost-effective approach to understand historical impacts, assess current disease pressures, and anticipate future risks. By systematically gathering input from experienced professionals, EKE bridges data gaps, informs spatial targeting of interventions, and complements limited empirical datasets (Authority, 2014; Hoffmann et al., 2007; Hemming, Burgman, et al., 2018; Hemming, Walshe, et al., 2018; Whittle et al., 2013). EKE has proven effective across diverse domains, from managing invasive species to modeling national-scale plant disease risk (Barryf et al., 2015; Wittmann et al., 2015;

Hughes & Madden, 2002; Thomas-Sharma et al., 2017) and represents an opportunity to synthesize epidemiological information for Pakistan's wheat sector.

Alongside EKE, geospatial network analysis offers another critical dimension to understanding plant health. The geographic distribution of pathogens and pests is shaped not only by climate and host presence, but also by their ability to disperse either naturally or through human-mediated activities such as seed exchange and equipment movement (Gunduz et al., 2016; Gent et al., 2019). Incorporating network analysis into geographic risk assessments allows for more realistic evaluations of spread pathways and has been successfully used to identify candidate surveillance priorities in potato systems across Ethiopia, Georgia, and other global contexts (Xing et al., 2020a, 2020b; Etherton et al., 2025).

This study leverages expert knowledge and spatial network analysis to improve understanding of large-scale epidemiological risks in Pakistan's wheat production system. The first objective is to map the spatial patterns of crop yield losses associated with 33 known wheat diseases and pests across the country's main wheat-producing districts, providing the first comprehensive national perspective on their impacts. In parallel, we evaluate the potential for local spread of emerging or re-emerging threats by applying cropland connectivity analysis, which accounts for landscape structure and linkages between production zones. We also examine the potential for (re)introduction of wheat pathogens through international trade and the domestic movement of seed and grain, identifying potentially vulnerable nodes across the wheat supply chain. Lastly, this work synthesizes expert perspectives on the current management practices and challenges associated with key wheat pests and diseases, highlighting areas of resilience as well as gaps in management efforts. Together, these approaches aim to inform national strategies for surveillance, preparedness, and targeted intervention, ultimately supporting Pakistan's broader goals of agricultural sustainability, food security, and economic resilience.

Materials and Methods

Study Area

This study focused on the major wheat-producing regions of Pakistan to ensure comprehensive geographic representation of the crop's production landscape and associated pest and disease pressures. Wheat was selected as the target crop due to its national importance and widespread cultivation.

To capture spatial variability in the knowledge elicitation, experts were invited from wheat-growing districts across all four provinces. But the core wheat belt, comprising central and southern Punjab and parts of upper Sindh, was prioritized due to its high production volume, Punjab alone contributes approximately 75% of national wheat output. Sindh contributes around 11–12%, mainly through canal-irrigated regions. Additional data were incorporated from key irrigated zones in Khyber Pakhtunkhwa

(KPK) and selected areas of Balochistan to ensure ecological and regional coverage. This spatial framework was essential for the implementation of expert knowledge elicitation (EKE) and for mapping wheat pest and disease risks at a national scale.

Expert knowledge elicitation

We developed an expert knowledge elicitation (EKE) framework structured in three stages, adapted from established EKE methodologies applied in plant health risk assessments (Anderson et al., 2021).

First stage: Expert selection and EKE Instrument Preparation

To ensure comprehensive and regionally informed input, a structured nomination and review process was conducted prior to the expert knowledge elicitation (EKE) workshop. Experts were identified by contacting all major institutions and stakeholders involved in wheat production and protection across Pakistan. These included the Department of Plant Protection, Plant Quarantine Division, CABI Pakistan, provincial agricultural research institutes, agricultural universities, seed companies, flour mills, and progressive farming networks.

Each organization was asked to nominate wheat experts with backgrounds in pathology, entomology, agronomy, plant breeding, or related disciplines. Along with the nominations, CVs were requested to evaluate the candidates' relevance and expertise. A four-member internal review team assessed all received CVs based on demonstrated experience with wheat diseases, pests, and field-level agricultural systems.

Candidates with limited relevance or insufficient field experience were excluded. Priority was given to individuals with extensive applied or research experience across different aspects of the wheat value chain. From the pool of nominees, 25 experts were shortlisted; 23 of them participated in the in-person workshop. The spatial representativeness of participating experts matched the geographic pattern of wheat production in Pakistan, with more experts in the main wheat-producing areas (Punjab, Sindh, Balochistan and KP). A full list of contributing institutions is provided in Supplementary Table S1.

The formal first stage of the EKE began with defining its scope and structure, led by a core organizing team comprising national wheat specialists and facilitators who were distinct from the selected participants. This internal team was responsible for shaping the focus of the elicitation process and ensuring its alignment with national wheat health priorities. Through a series of planning meetings, we developed a comprehensive list of priority diseases and pests, including eight high-impact threats causing major on-field losses, 26 species responsible for minor but recurring damage, and seven post-harvest pathogens and pests. We then identified which geographic information could provide us with a broad perspective of the national wheat crop health status, which could be quickly acquired through

EKE. In general, our EKE addressed geographic information needed for understanding the local impact, potential spread, and available management for wheat diseases and pests.

Structure and Content of the EKE Instrument

Following the prioritization of target threats and geographic determinants, we developed a structured EKE instrument comprising seven thematic sections to systematically capture expert input (Supplementary Material 1). Each section was designed to gather information relevant to understanding the distribution, impact, and management of wheat diseases and pests across Pakistan's major production zones.

The first section focused on eight high-priority diseases and pests, collecting expert estimates of yield losses using annotated maps, and evaluating the influence of climate change and key agronomic factors on disease pressure. The second section addressed 33 minor but nationally or provincially relevant threats, including post-harvest pests, with experts rating familiarity and estimated losses across provinces or at the national level. The third section explored stakeholder interactions in the wheat seed system, capturing the direction and intensity of material and information flow among policy, research, industry, and farmer groups (Garrett, 2021).

The fourth section examined seed and grain exchange routes, both formal and informal, across provinces and international borders to assess potential spread pathways for seedborne pests. The fifth section evaluated certified seed use, wheat varietal diversity, and pesticide application practices across different cropping systems. The sixth section gathered expert perspectives on improving wheat health over 5 and 20year horizons, and the seventh captured feedback on the elicitation process itself.

The instrument also included seven close-ended questions specifically designed to assess the spatial and thematic experience of each participant. These experience-based metrics, captured through self-reported years of involvement across regions and topics, were used to weigh participant responses in proportion to their relevant expertise, ensuring that input from more experienced individuals had greater influence in the interpretation of results.

Second stage – EKE workshop

A two-day in-person EKE workshop was conducted on June 16–17, 2022. The workshop began with an overview of the study objectives, the EKE methodology, and examples from previous EKE applications. Organizers then explained each question in the EKE instrument, ensuring that all doubts were addressed before participating experts provided their answers. For each question in the EKE instrument, experts first provided answers individually. We then grouped participating experts into small teams of 4 to 6 individuals. For some questions in the EKE instrument, each small team of participating experts reported their collective answers. Each group then discussed their collective responses with all other groups. This participatory approach engaged experts to reach a consensus in their answers and facilitated the discussion of potential discrepancies through dynamic dialogue and open debate. Each expert or leader of a small team manually documented their answers on a hard copy of the EKE instrument given to each expert. Additionally, for questions addressing spatial patterns, we provided experts with maps outlining the districts of Pakistan, where they colored each district according to a predefined color legend for the question. We then digitized all responses in a tabular format (Data S1).

Third stage - Data analysis of expert knowledge

Despite potential variations in expert opinions and a lack of precise geopositioning, EKE provides a valuable, rapid, and comprehensive tracking of risk factors associated with epidemics or pest outbreaks nationwide. In the context of plant health assessments, EKE is particularly valuable in low-income countries, for epidemiological factors that are costly or challenging to estimate or document, or where an enough number of experts can assess those factors. The EKE conducted in Pakistan met these criteria.

For close-ended questions, we analyzed both individual responses and the collective responses generated by small teams of experts. Since these two types of responses represent ordinal data, we calculated the arithmetic mean in responses across experts or small teams to indicate the expected central tendency of each risk factor being studied. We also calculated the standard deviation of individual or collective responses to provide a quantitative measure of the level of uncertainty in each risk factor. We considered a confident consensus answer when the opinions by many experts resulted in a low standard deviation of a risk factor. While individual assessments may exhibit more variation in responses, collective answers might be biased towards a few individuals with strong behavior in a group (Hemming, Walshe, et al., 2018). We compared the mean values of each risk factor generated by individual responses with those from collective responses. We additionally estimated the total years of experience reported by experts as a relative proxy for confidence in our analysis outcomes. For open-ended questions, we analyzed individual responses only qualitatively.

For answers with geospatial information (e.g., crop loss estimates or seed use), we matched estimated statistics of the EKE outcomes at the district level with their corresponding standard polygon geometries from the rgeoboundaries package (Runfola et al., 2022). We also used the bivariate mapping approach in the biscale package to compare crop loss estimates with the number of responses. For visualizing the geographic networks of wheat exchange, nodes represented the approximate centroids of geographic locations, and the directed links indicated expert-reported movement of wheat commodities between locations. For stakeholder interaction networks, nodes indicate stakeholder types and links indicate a type of interaction between stakeholders (communication or wheat exchange). We performed all analyses and generated visualizations in R 4.3.3 using the following packages: ggraph, ggplot2, igraph, sf, terra, and tidyverse. Code, data, and detailed assumptions to reproduce these analyses are available at https://github.com/GarrettLab/Wheat-health-in-Pakistan.

Mapping wheat cropland connectivity

We used the geohabnet R package to map wheat cropland connectivity in Pakistan.

We obtained geographic information on wheat cropland distribution in 2023 from the AsiaWheat dataset. This raster layer represents the area fraction of winter wheat at 250-m spatial resolution in Asia. We projected the coordinate reference system (CRS) of this cropland-fraction map to the standard CRS EPSG:4326. We selected locations with 5% wheat coverage. The mean() function evaluates the importance of each host location in a region based on the relative likelihood of spread of a pathogen or pest. We aggregated cropland-fraction maps to km and final maps were masked outside Pakistan.

Evaluating introduction risks through international trade patterns

The alarming emergence of wheat blast in Bangladesh in 2016, likely originated from South America, suggested that human-mediated dispersal possibly played a key epidemiological role in the geographic spread of this destructive disease at a transcontinental scale (Islam et al., 2016) [ADD ALSO https://doi.org/10.1146/annurev-phyto-080417-050036]. This concerning situation motivated us to evaluate possible scenarios for the unintentional introduction of the wheat blast pathogen (*Magnaporthe oryzae* pathotype *Triticum*, MoT hereafter) into Pakistan through the international trade of wheat commodities. We previously developed a general framework to assess human-mediated introduction risk of plant pests into crop-growing countries [https://www.garrettlab.com/giraf/]. We adapted this introduction risk assessment framework to specific input data as briefly described here. We calculated the average international trade volume of wheat commodities (metric tons) over the last decade, using the 2013-2022 bilateral import reports from the World Trade Organization (WTO) database [https://stats.wto.org/]. This introduction risk analysis focused on wheat seed (HS100191) as a putative main pathway for long-distance dispersal of MOT (Maciel et al., 2014) and excluded processed wheat commodities (bran, flour, and germ). We also estimated the average harvested area of bread wheat from 2013 to 2022, from the FAOSTAT database (https://www.fao.org/faostat/en/#data/QCL). We assumed that harvested area is a relative proxy of within-country host availability for the wheat blast pathogen since bread wheat is its major host. We compiled information about the geographic distribution of MoT within countries from CABI Compendium (Islam, 2016) and publicly available reports. We considered that pathogen-specific phytosanitary measures are not imposed on international trade in the analysis. We combined these geographic risk factors to evaluate the introduction potential of MoT to all wheat-producing countries, and a focused analysis for Pakistan. Although we focused on MoT as an example of understanding its potential spread through international commodity trade, this analysis can be applied to evaluate the introduction risk of other seedborne or seed-transmitted wheat pathogens or pests. For example, if primary inoculum is introduced in Pakistan and in absence of phytosanitary measures, a possible pathway for long-distance dissemination of MoT within the country would be the domestic trade of wheat seed.

Results

Spatial Patterns of Crop Losses Caused by Wheat Diseases and Pests

First, we report expert assessments of the geographic distribution of crop yield losses caused by eight major diseases or pests at a district level (2018-2022). Most experts estimated stripe rust as the disease causing the highest mean losses in wheat yield nationally (Figure 1) dominating central and eastern Punjab as well as parts of upper Sindh. Leaf rust exhibited widespread moderate to high mean losses, particularly concentrated across southern and southeastern Sindh. The disease impact extended into central and eastern Punjab with moderate losses. (Figure 1). Stem rust losses were medium (~1.5–2%) across much of Pakistan, especially in central and southern Punjab, Khyber Pakhtunkhwa, and southern Sindh. Aphid-related losses were moderate (1.5–2.0) across central Punjab and Sindh, with low losses (<1.0) in Balochistan and Khyber Pakhtunkhwa. Armyworm losses were more scattered, with moderate losses (1.5–2.0) in some districts of central and southern Punjab and northeastern Sindh, but low to negligible in other districts. Mean losses caused by karnal bunt were moderate (1.5–2.0) in southern Sindh and parts of northern KPK, but most of Balochistan and parts of Punjab showed very low losses. Loose smut showed the lowest overall mean losses in the country, with a few districts with medium losses in northern Punjab and southern Sindh.

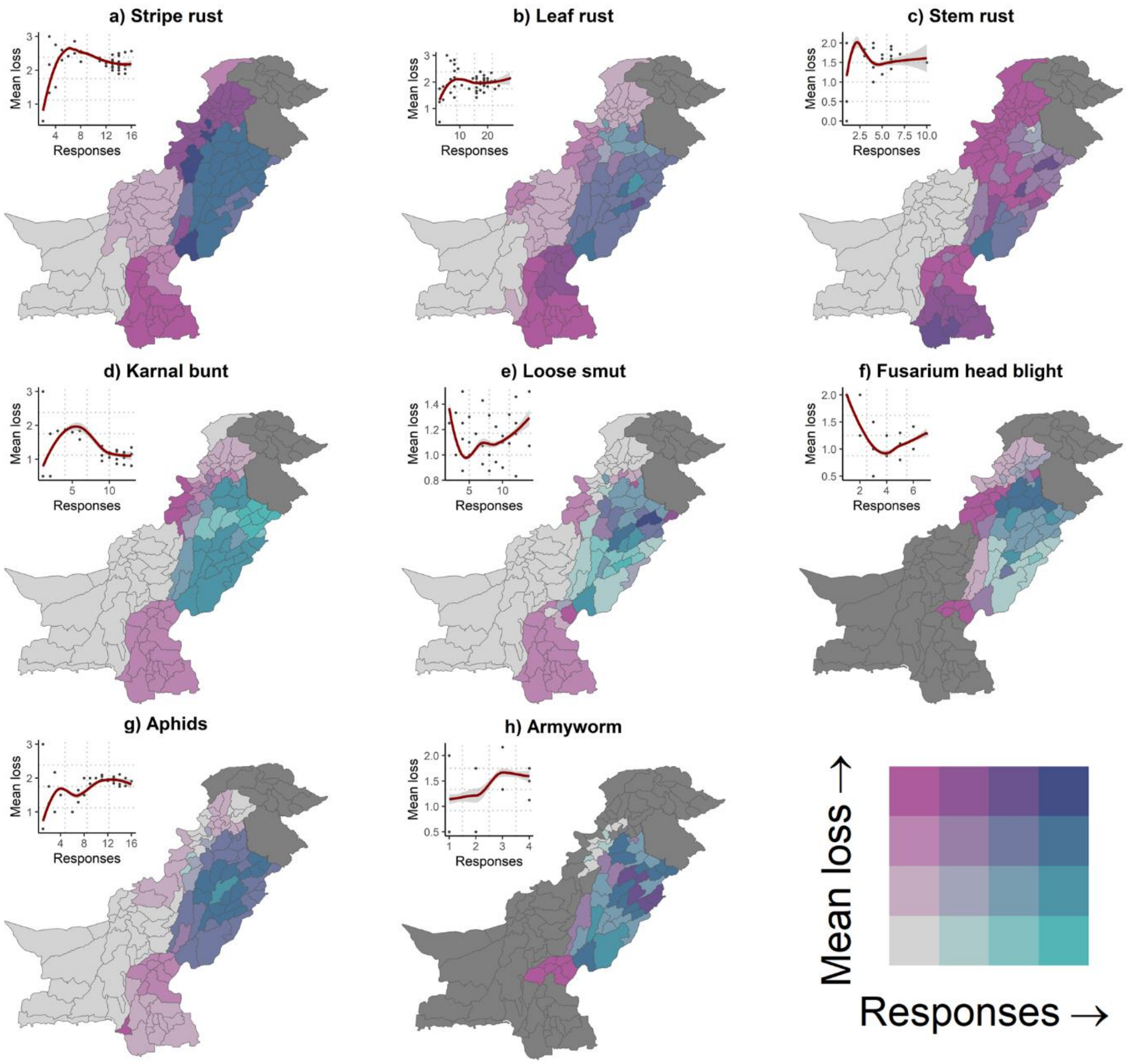

Figure 1. Expert-estimated crop losses (%) caused by eight major wheat diseases and pests in 2018-2022. Note that the levels in the bivariate color legend are specific to each disease or pest and are proportional to the inset of each panel. For example, the darkest blue in the legend indicates a region with high mean crop loss (~3%) and many expert responses (16) for aphids. Districts in dark grey are regions where no experts responded in the expert knowledge elicitation (EKE) instrument.

Importance of Driving Factors in Yield Losses Caused by Diseases and Pests

To understand the underlying causes of wheat disease and pest outbreaks in Pakistan, we assessed expert-elicited perceptions of the relative importance of seven main agronomic and biological drivers. We analyzed expert responses separately from five small groups and from 28 individual experts, covering the same eight major biotic threats in the section above. Experts ranked each main driver into four importance categories: high (assigned a score of 10 for quantitative comparison), medium (5), low (2.5), or no importance (0).

In both collective and individual responses, experts ranked climate change as the most influential driver across all pests and diseases (Figure 2). This strong consensus indicated a high mean influence of climate change on leaf rust, stripe rust, wheat aphid (each with a maximum score of 10), stem rust (8.5), Karnal bunt (9), and armyworm (8.1). This finding is quantitatively supported by the generally low standard deviations (e.g., 1 for leaf rust, stripe rust, and aphids) in both collective and individual responses. Pathogen sub-populations also received high influence scores, especially for the major fungal diseases, leaf rust, stem rust, stripe rust (each ~8.5), and Karnal bunt (8.75). The influence of subpopulations was perceived lower for the two major pests included in the analysis, armyworm and wheat aphids. Pesticide use, resistance gene deployment, and propagule from alternative hosts all were perceived to have an intermediate influence depending on the target pest or disease. Notably, resistance gene deployment had moderate influence for rust diseases (means ~5.5), while pesticides were seen as moderately influential for loose smut (4.5) and aphids (3.5). While sowing time was moderately important for wheat aphid (7.5) and leaf rust (6.0), it was less relevant for Karnal bunt and Fusarium head blight (4.4). Fertilization was consistently rated as a minor driver (2.5–3.8) for most fungal pathogens and pests, with the exception of wheat aphid (8.5).

The individual expert responses largely supported group findings but provided greater nuance and variation, as reflected by broader distributions and standard deviations (figure: 13). Climate change and pathogen sub-populations remained the most influential driver, with the highest mean scores for leaf rust, stripe rust, and aphid. This confirmed the group consensus, yet standard deviations were slightly higher.

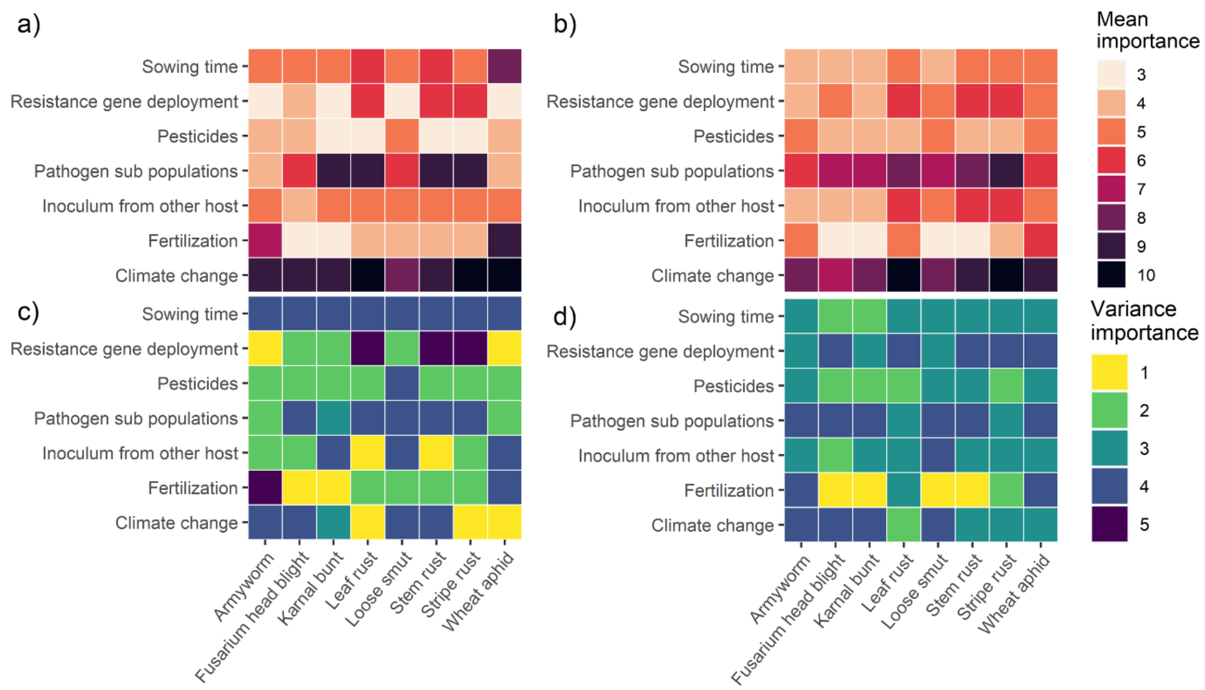

Figure 2. Expert-estimated importance of epidemiological factors driving yield losses of major diseases and pests in Pakistan. a) Mean across group assessments, b) mean across individual assessments, c) variance across group assessments, and d) variance across individual assessments.

Geographic Patterns of Certified Wheat Seed Use

We assessed the spatial distribution of certified wheat seed use across Pakistani districts based on expert knowledge. In general, there was a strong agreement of individual perspectives on wheat seed use with the collective opinions provided by expert groups (Figure 3).

Group-based assessments indicated that the mean certified seed use ranged from 10% in several districts (e.g., Awaran, Barkhan, Chagai, and parts of Balochistan) to over 33% in high-adoption districts such as Lahore, Gujranwala, Hafizabad, Sahiwal, Kasur, and Sheikhupura (Figure 3). These districts consistently showed low standard deviations (≤5%), indicating strong agreement among group participants about high certified seed usage. Moderate adoption rates (20–30%) were observed in districts like Dera Ghazi Khan, Khanewal, and Jhang, but these often came with greater variability.

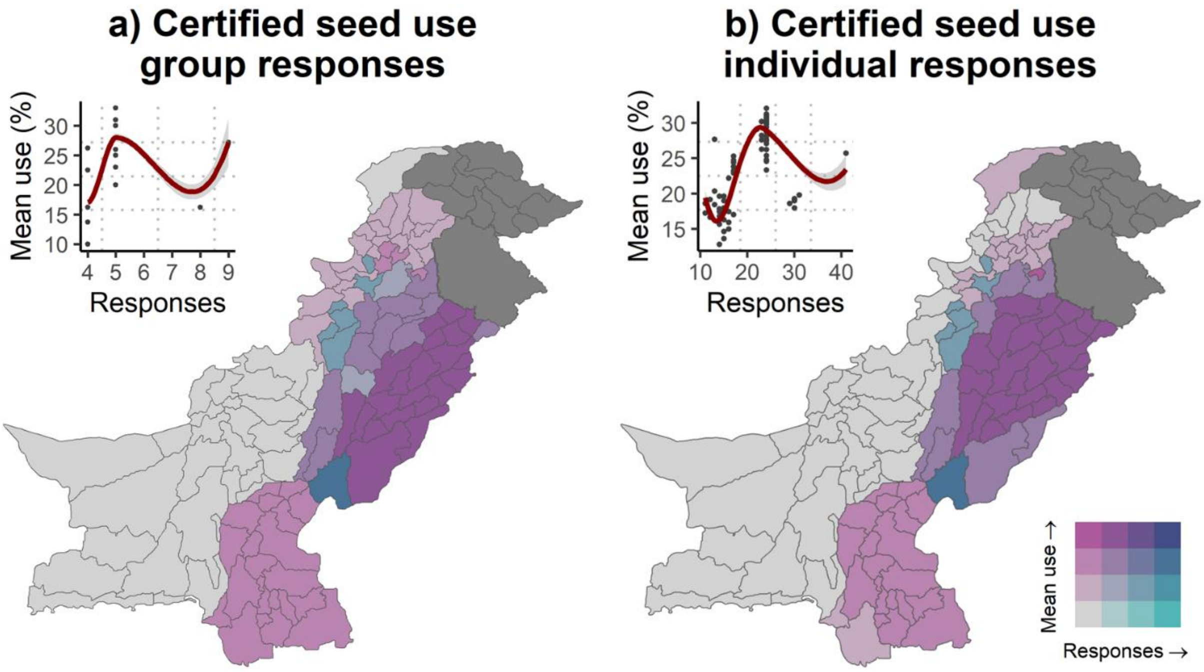

Figure 3. Mean use percentage of certified wheat seed based on expert assessment.

The individual-level dataset corroborated many of the patterns observed at the group level but also revealed greater heterogeneity in certified seed use. Districts like Faisalabad, Gujranwala, Hafizabad, and Jhang had mean certified seed use exceeding 30%, with very low standard deviations (<7), reinforcing their status as certified seed use hubs. Meanwhile, low-use regions such as Lasbela, Kohlu, and Dera Bugti consistently showed mean use levels around 12–15%, aligning with group-level observations. However, individual-level data exhibited higher standard deviations in several districts, such as Lodhran, Rawalpindi, and Bahawalnagar (Figure 3).

Geographic Networks of Seed and Grain Exchange

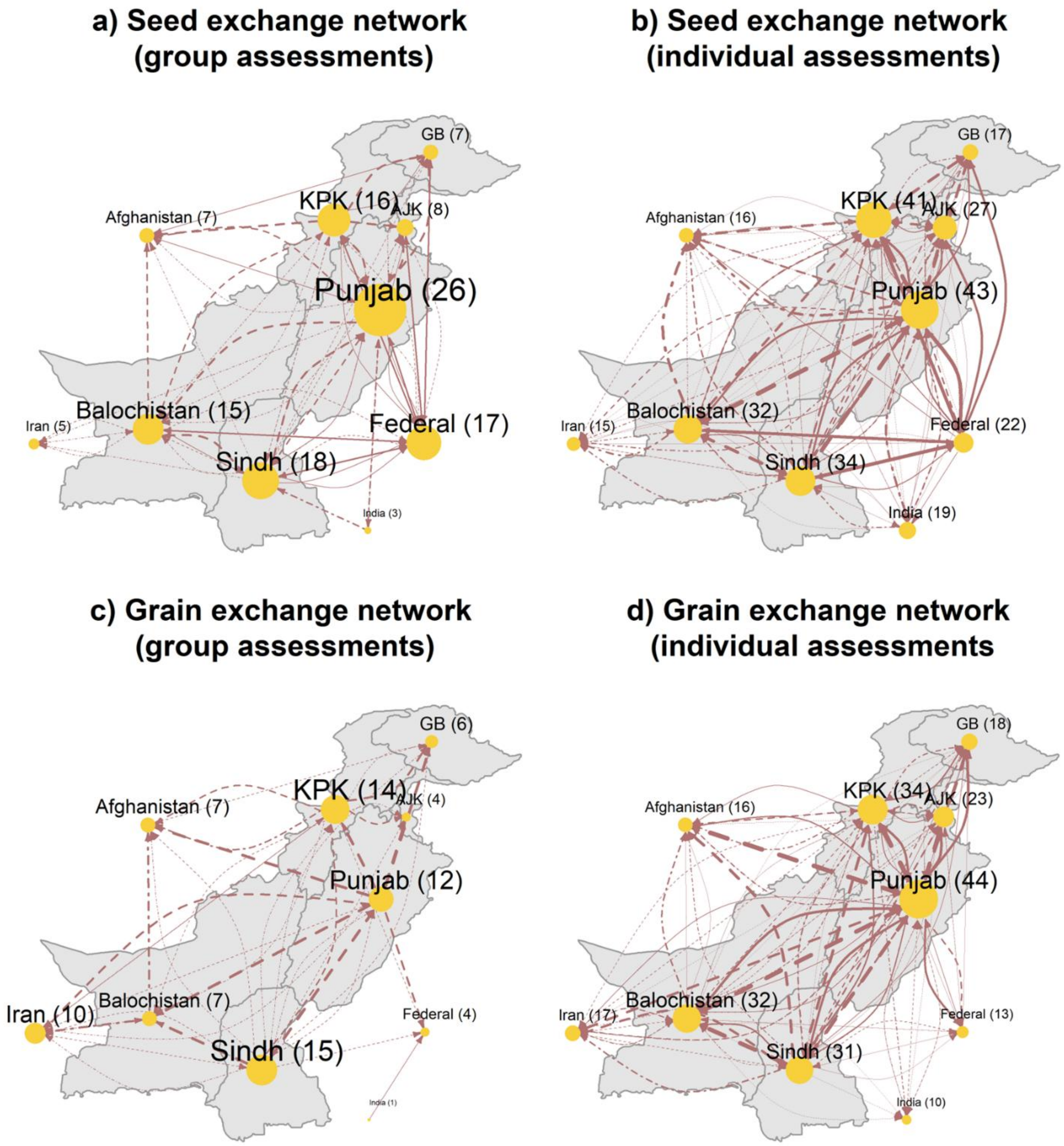

Figure 4. Geographic exchange of wheat seed and grain in Pakistan reported by 5 groups and *29 experts. Node size and label size are proportional to the number of connections of a region, as indicated within parenthesis. Line types correspond to three categories of seed or grain exchange (solid = formal-only trade, dashed = informal-only trade, and dotdash = both types of trade). Abbreviations: AJK - Azad Jammu & Kashmir, KPK - .*

Seed Exchange Networks

Experts reported a highly interconnected network, in which wheat seed exchange occurred among provincial, national, and international agroecosystems (Figure 4). Based on collective expert responses, this network consisted of 61 trade links (25% only formal, 34% only informal, and 41% both types). Based on individual expert responses, this network consisted of 133 trade links (29% formal only, 40% informal only, and 30% both types). We used the number of trade links connected to a node in this network (i.e., node degree) as a measure of the relative importance of each location in the seed exchange. In the group responses, the relative importance of each location is Punjab > Sindh > Federal > KPK > Balochistan > Azad Jammu & Kashmir (AJK) > Gilgit Baltistan (GB) > Afghanistan > Iran > India. In the individual responses, the relative importance of each location is Punjab > KPK > Sindh > Balochistan > AJK > Federal > India > GB > Afghanistan > Iran. In both types of responses, Punjab is reported as the most active hub in seed exchange, acting both as a source and a recipient. Punjab maintained formal and informal exchange of wheat seed with all other provinces, Afghanistan, India, and Iran.

KPK and Sindh also played a major role in the bidirectional flow of wheat seed, either formally or not, but acted as net seed sources, being twice as likely to provide seeds rather than receive them. The Federal territory served as a key trade bridge between more peripheral regions such as GB and AJK, through formal and informal seed exchange. Seed movement of wheat seeds from or to neighboring countries was less likely than domestic seed trade. India was twice as likely to export wheat seed to Pakistan compared to importing it from Pakistan. Pakistan was twice to four times more likely to export wheat seed to Afghanistan and Iran than to receive it from them. Overall, our analysis provides evidence of the co-existence of formal dissemination channels along with farmer-led movement of wheat seed, either domestically or internationally.

Grain Exchange Networks

In collective responses, the grain exchange network consisted of 40 trade links (3% only formal, 30% only informal, and 67% both types). In individual responses, this network had 119 trade links (32% formal, 27% informal, and 41% both types). Despite individual expert opinions indicated a relatively high proportion of formal-only trade links (~30%), the consensus response reported by experts suggested few formal-only trade links (~3%). In the group responses, the relative importance of each location is Punjab > Sindh > Federal territory > KPK > Balochistan > AJK > GB > Afghanistan > Iran > India (Figure 15). In the individual responses, the relative importance of each location is Punjab > KPK > Balochistan > Sindh > AJK > GB > Iran > Afghanistan > Federal territory > India. In both response types, Punjab was a major trade hub of wheat grain acting as a recipient and a source. Punjab had trade connections with every region considered in this study (except with India as indicated by the consensus response).

In either response type, experts reported that Sindh was three to six times as likely to act as a major source of wheat grain than being a recipient. Likewise, KPK was about twice as likely to serve as a net grain source. The remaining seven regions were likely net recipients in this trade network of wheat grain, emphasizing strong inter-regional trade dependencies. In terms of international trade, neighboring countries (Afghanistan, India, and Iran) acted mainly as recipients of wheat grain from different regions of Pakistan. In both individual and collective assessments, these international trade links primarily represented informal channels, although few experts individually reported formal exports to India.

Networks of Information and Plant Material Exchange between stakeholders

The analysis of stakeholder interactions in Pakistan's wheat sector revealed intricate and densely connected networks for both information exchange and planting material movement.

The information network was characterized by multiple strong ties between different stakeholder categories (Figure 5). Central to the network were the farmer associations, seed users, seed dealers, policy makers, and research institutions (both national and international). Farmer associations and seed dealers stood out as major conduits, linking both upstream (research, policy) and downstream (users, producers) entities. The strong bidirectional flows between these actors and the public and private food sectors reflect their dual roles in information dissemination and feedback collection. National research institutions and NGOs also played critical bridging roles, interfacing with multiple actors across sectors, including the international research community and specialized seed producers, suggesting their pivotal influence in shaping evidence-informed decision-making.

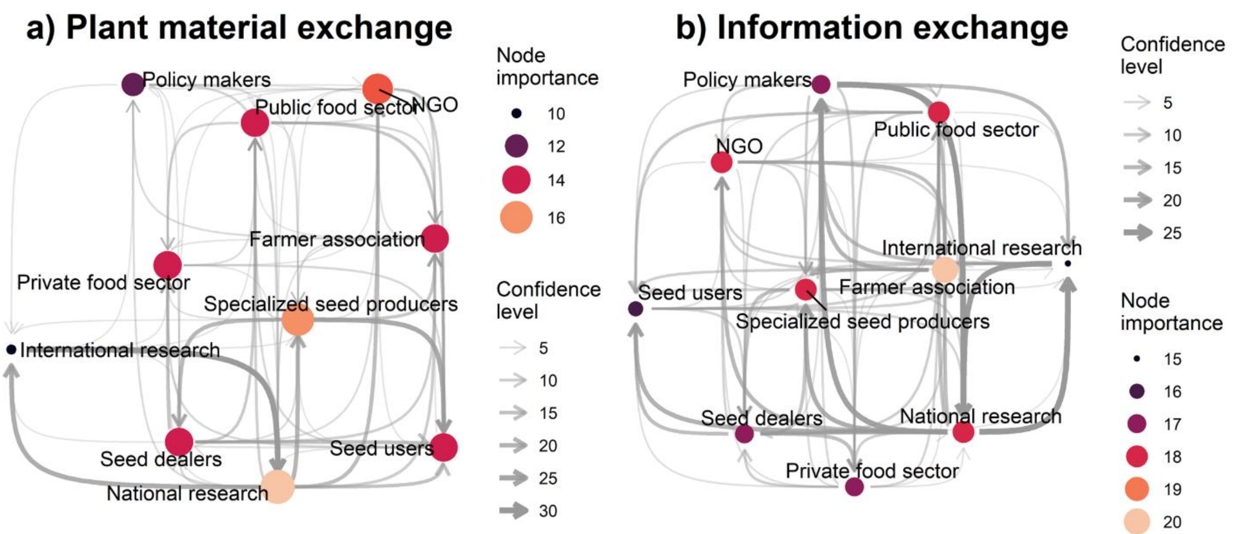

Figure 5. Exchange of management resources between stakeholders of the wheat system in Pakistan. Node importance indicates the total number of connections from or to a stakeholder. Confidence level is the number of experts that indicated the existence of a connection.

The plant material (PM)/seed exchange network illustrates the directional flow and intensity of seed transactions among key stakeholder groups involved in Pakistan's wheat system. Seed users, farmer associations, seed dealers, national research institutions, and public food sector emerge as the most influential nodes based on (higher node centrality/degree). The seed users appear as the primary recipients of seed materials, connected to nearly all other stakeholders. Farmer associations and seed dealers show high centrality, acting as intermediaries between formal institutions (like national research or NGOs) and end users. The national and international research entities, along with specialized seed producers, maintain strong directional ties toward public and private food sectors, policy makers, and seed dealers, indicating their upstream role in the seed development and dissemination chain.

The public and private food sectors are both well-connected and act as bridges between regulatory/policy-making actors and operational-level stakeholders, such as dealers and users.

Wheat Cropland Connectivity in Pakistan

The cropland connectivity analysis for wheat across Pakistan revealed a highly uneven spatial distribution of connectivity intensity and align closely with landscape patterns of wheat production (Figure 18). Connectivity scores indicated regions with greater or lesser potential for disease or pest spread based on the density and continuity of wheat cultivation.

A distinct north-to-south corridor of high cropland connectivity was observed, extending from the wheat-intensive districts of northern Punjab through central Punjab, reaching into parts of southern Punjab and northern Sindh. Connectivity values in this zone frequently approached the maximum of the scale (0.8–1.0), forming a contiguous belt of densely connected wheat fields. Central Punjab, including districts such as Gujranwala, Faisalabad, and Sahiwal, exhibited some of the highest connectivity scores nationwide. Moderate cropland connectivity was evident across upper Sindh, including districts like Sukkur and Ghotki, and parts of lower Khyber Pakhtunkhwa. Connectivity scores here ranged from approximately 0.5 to 0.7, suggesting that while wheat cultivation remains relatively important, the fields are less continuously distributed compared to central Punjab. Conversely, low connectivity regions were prominent across western Balochistan, the northern mountainous areas of Gilgit-Baltistan, and the upper reaches of Khyber Pakhtunkhwa. These areas consistently displayed connectivity scores between 0.3 and 0.4.

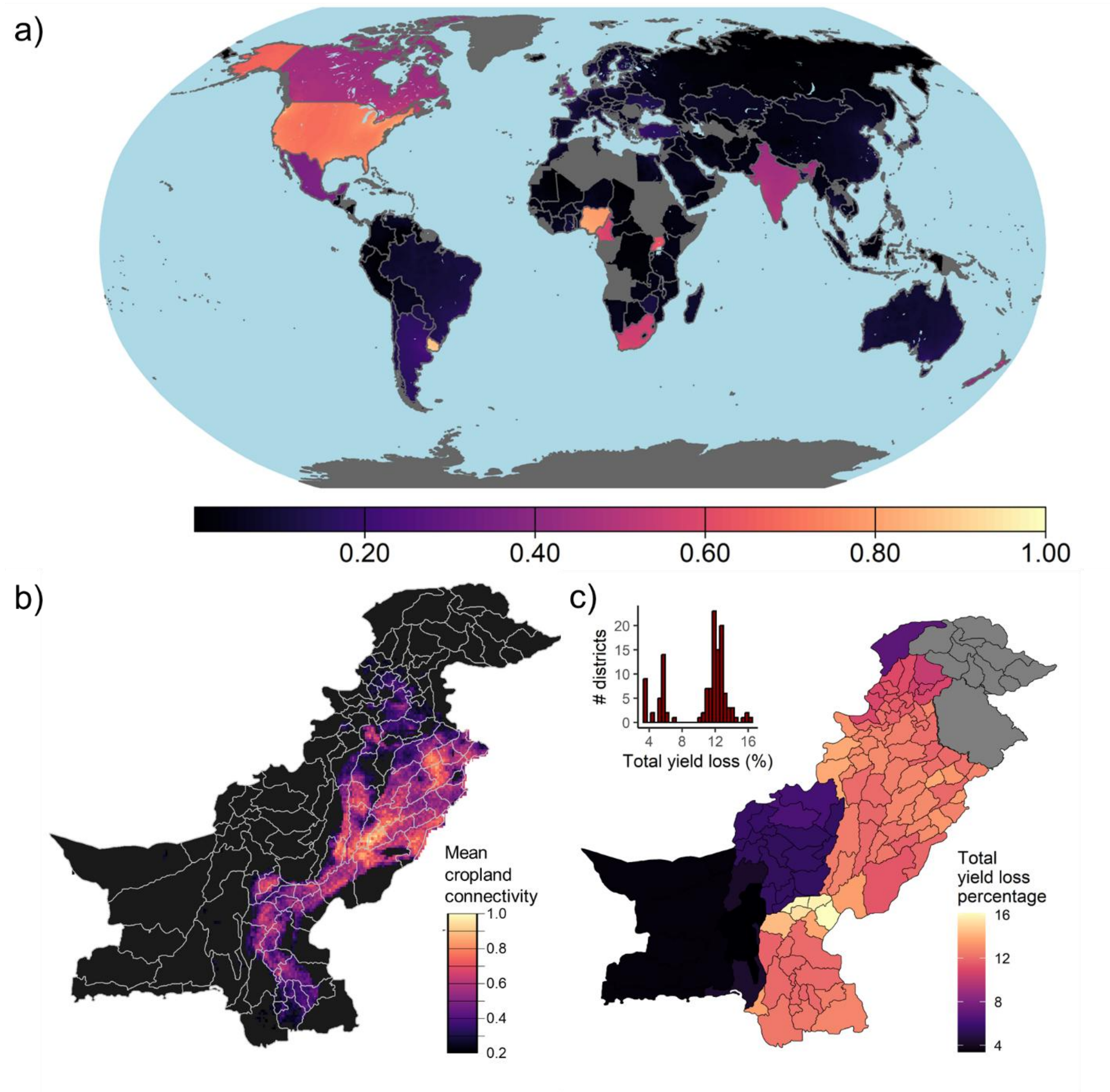

Figure 6. a) Relative risk of wheat-producing countries to the potential introduction of Pyricularia oryzae pathotype *Triticum. This global analysis presents a possible scenario in which the international spread of the pathogen is unintentionally mediated by the formal trade of wheat seed to countries where its main host is available (bread wheat), and no pathogen-specific phytosanitary measures are implemented. The mean cropland connectivity score indicates the relative importance of locations for the potential spread of wheat-specific pathogens and pests. b) The cumulative yield losses (%) caused by the eight major wheat diseases and pests based on the arithmetic average of individual expert assessments.*

Discussion

This study provides an expert assessment for a set of established wheat diseases and pests in Pakistan. This assessment indicates that common hotspots of wheat crop losses caused by stripe rust, leaf rust, and aphids occur in the main wheat-producing districts (Figs. 1 and 6). This finding is consistent for these major biological threats. However, loose smut, stem rust, Fusarium head blight, and armyworm showed specific geographic patterns. Experts reached a consensus that climate change is a primary driver in the increase of crop yield losses caused by these eight targeted diseases and pests. Another contributing factor to wheat yield losses is the sub-populations of pathogens, particularly those causing leaf, stem, and stripe rust. Next, experts evaluated risk factors influencing pathogen or pest spread. Certified seed use is reported to be above 25% in Punjab, where yield losses across the eight major diseases and pests were 12-15% (Figs. 3 and 6). Informal movement of wheat seed (70-75%) and grain (68-97%) contributes a large share of the national trade networks (Fig. 4), highlighting the vulnerability of seed systems to the potential spread of pests and pathogens via this pathway.

Together, these findings provide a multifaceted perspective of Pakistan's wheat health landscape and highlight how geographic factors may influence disease progression and pest spread. This collective expert knowledge provides a rapid approach to understanding the potential spread of pests and pathogens on a large scale and key starting points for strengthening national surveillance and management strategies. This expert-based perspective can also help stakeholders to plan where the implementation of more objective (and perhaps more expensive) approaches to acquiring information is more effective for future detailed studies. Below we discuss how the findings of this study have important implications for farmers, research organizations, and the overall value chain of wheat production.

Perspectives on wheat yield losses and their drivers. In our analyses, crop yield losses reflect regional patterns of disease distribution and highlight Pakistan-specific trends. Consistent with previous studies indicating a geographic expansion of rust pathogens owing to increasingly warming conditions (KHANFRI et al., 2018; Sufyan et al., 2021), expert assessments suggest that climate change plays a major role in wheat yield losses in combination with major diseases and pests in Pakistan. Increasing high temperatures, shifting rainfall patterns, and more frequent extreme weather events have been recently reported in Pakistan (Tuladhar et al., 2023). These climate-driven changes are likely to facilitate reproduction of pathogens and pests, extend the seasonal window for disease and pest development, expand a species' geographic range, and modify virulence of some pathogens (Jonathan & Mahendranathan, 2024; Lahlali et al., 2024).

Pathogen sub-population was among the top two factors driving wheat yield losses, reflecting perceived concerns about potential erosion of disease resistance in currently used cultivars. Population dynamics of *P. striiformis*, *P. triticina*, and *T. indica* have been extensively studied in Pakistan (Aasma et al 2022, Fayyza et al. 2008, Khan et al 2020, Khan et al 2021), but other wheat pathogens or pests require further attention (Khan et al 2019). Importantly, the northern Himalayan region of Pakistan is part of the putative center of genotypic diversity of the yellow rust pathogen (Ali 201), making long-term epidemic management in the region challenging (Khan et al 2020). Acquiring more geographic information on pathogen populations will aid national breeding programs, strategic deployment of resistant cultivars, and enhanced understanding of seasonal dynamics of optimal infection conditions.

Experts also consistently recognized the moderate importance of fertilization (particularly in combination with wheat aphid and armyworm), sowing time (wheat aphid, stem, and leaf rust), and the deployment of resistance genes (leaf, stem, and stripe rust) on wheat yield losses. Fertilization is likely to influence arthropod pests, but a more complete evaluation is needed for Pakistan (Khan et al. 2021). Late sowing date (i.e., December) is reported to increase wheat aphid populations in Pakistan (Aslam et al 2005), so early planting is key to avoid conditions favorable for infection (Shahzad et al 2013). Planting date has been an important predictor of disease severity caused by leaf and stem rust in many countries (e.g., Naseri and Sasani 2020, Moschini and Pérez, Gebrel et al 2018), reinforcing expert opinions in Pakistan. In collaboration with CYMMIT, the formal release of wheat varieties has allowed gene resistance deployment (5-10% disease severity reduction), particularly against leaf and stripe rust, in South Asia (including Pakistan) and East Africa (CITATIONs). Effective deployment of resistant varieties for wheat diseases remains challenging due to various factors, such as continuous evolution of pathogens, farmer preferences, and lack of awareness (Singh et al 2025, Pink and Hand 2002). Pesticide use and inoculum from hosts other than wheat were generally considered to have a low influence on most diseases and pests, possibly indicating reduced chemical efficacy (Khan et al., 2021) and low pathogen sharing.

Estimated crop losses from multiple diseases and pests overlapped in core wheat-producing districts like Punjab and Sindh. These estimates highlight a significant vulnerability in these intensively cultivated areas, where dense monocultures, narrow genetic diversity, and heavy agricultural inputs are common. Regions such as Balochistan and parts of the tribal belt exhibited consistently low reported losses and few expert responses. This finding may be partly attributed to climatic constraints to pathogen development, reduced wheat productivity, and lower surveillance efforts (Ghulam Murtaza Safi et al., 2014)(Akhter & Mirza, 2006).

Perspectives on seed health management. In this paper, we characterize for the first time two key components of the wheat seed system in Pakistan as proxies for understanding the national status of seed health. First, certified seed adoption decreases the likelihood of pathogens or pests being introduced and established at the farm, district, and national levels. Districts with a high mean in certified seed use, like Lahore and Gujranwala, had a lower variation across analyses, highlighting strong agreement between group and individual expert assessments. High certified seed adoption reflects a greater influence of formal seed systems in these regions, possibly underpinned by strong institutional support, which enables more consistent varietal deployment (McEwan et al., 2021). Districts like Lodhran or Khanewal had moderate certified seed use, but expert responses indicate high variability, likely reflecting uneven adoption patterns or extension support. Districts with low certified seed use, particularly in Balochistan, had fewer expert responses, indicating higher uncertainty. Future studies in these regions could focus on strategically improving quality-assured seed adoption, farmer outreach (Rai et al., 2020) and their impact on national management success.

Second, seed deployment systems are a key conduit to allocating desirable crop technologies such as high-yield wheat varieties. Characterizing the domestic and international movement of wheat seeds is also relevant for understanding the possible unintentional spread of seed-transmitted wheat pathogens. Seed-mediated transmission is an important epidemiological process for many wheat pathogens. Over 39 wheat pathogens are associated with wheat seed (seven bacteria, 28 fungi, a nematode, and three viruses), and notable examples include the bunt pathogens (*Tilletia* spp.), Fusarium head blight (*Fusarium* spp.), and wheat blast (Bockus et al 2010).

Our spatial network analysis identifies important patterns in the formal and informal exchange of wheat seed and grain across Pakistan. The formal system of seed deployment resulted from a combination of three approaches (Siddiqi et al., 2024a) (Ali, 2013). i) Punjab Seed Corporation is a private enterprise that commercializes a single variety to farmers. ii) A community-based seed approach is led by CYMMIT, where farmers are trained to multiply seeds based on seed certification standards. iii) A farmer seed approach includes a registered certification department, where farmers are linked with companies or government entities to multiply seed together. Punjab appeared as a major hub for seed and grain movement, having many links with other provinces. This result is expected since Punjab is the country's largest wheat-producing region, and many growers rely on private or governmental seed supply.

A large share of seed exchange took place through informal channels among farmers, emphasizing how informal systems likely fulfill critical gaps in varietal access in many rural areas (Tu et al., 2024). However, informal seed exchange increases uncertainty about seed health and may unintentionally facilitate the geographic translocation of seed-associated pathogens and pests (Hernandez Nopsa et al 2015). This epidemic potential mediated by seed movement is exemplified by the regional spread of *Tilletia indica* in South Asia in the past forty years (Singh et al 1989). Indeed, this fungal pathogen has a high quarantine importance globally, preventing international trade of wheat seed from invaded countries, including Pakistan (Bishnoi et al 2020). Our findings highlight the newly discovered roles of KPK and Sindh as net seed sources and the Federal Territory as potential strategic mediators in the seed system. Importantly, the likely roles of these locations as trade hubs, sources, or bridges were very similar in both the formal and informal systems.

Our analysis of the wheat grain network reveals that informal grain trade occurred between most provinces, particularly from large production zones such as Punjab and Sindh, toward other provinces. Market regulation and post-harvest quality assurance are potential key challenges in these grain systems, given the large contribution of informal exchange. Informal grain exchange may increase the uncertainty of transporting seedborne pathogens or storage pests. However, the informal movement of wheat grain for consumption does not directly translate into seedborne disease transmission. Together, the seed and grain networks underscore the need for a nuanced management approach that mitigates the potential movement of pathogens and pests in the national wheat system. Based on lessons learned from other agroecosystems (e.g., Andersen Onofre et al 2021), a hybrid management approach would be key to effectively addressing unintentional phytosanitary issues in both formal and informal seed exchange channels. Enhanced seed certification in formal systems, greater phytosanitary control of seed-transmitted pathogens, seed health testing in informal settings, and increased farmer awareness are among key opportunities to reduce uncertainties in seed transmission risk. While we focused on the presence or absence of seed exchange, future studies could include characterizing the frequency and volume of seed movement.

Perspectives on stakeholder networks. Stakeholder networks are crucial for the successful dissemination of management resources, whether breeding technologies or information about them (Garrett 2021). Characterizing past interactions between stakeholders allowed us to identify key roles of stakeholders in information sharing and the exchange of plant material. Most experts indicated a reciprocal exchange of information and plant material between national and international research stakeholders (Fig. 4), a desired component in these types of networks (Bishaw & Turner, 2008). Policy makers are likely to serve as net sources of plant material and information to other stakeholders, although few experts reported these connections. Seed users and the private food sector are likely to be net recipients of plant materials from any stakeholders. NGOs, seed dealers, specialized seed producers, and the farmer association serve as trade hubs, mutually exchanging plant material with other stakeholders. Experts reported that, in the information exchange network, all stakeholders are likely to have mutual interactions. This finding suggests that management information sharing among stakeholders is more active than the trade of plant material. Most experts also agreed that national research institutions serve as a primary hub of information sources for other stakeholders, reaffirming their entrenched position as a top-down disseminator of scientific and regulatory information (Moreddu & Poppe, 2013).

Previous studies have characterized stakeholder interaction networks of agricultural research systems (Hellin & Camacho, 2017; Muijs et al., 2011), but a key contribution of our analysis is the system perspective for epidemic management based on network structures. Identifying stakeholder roles in these networks provides valuable insights for planning targeted interventions to manage epidemic progression or pest invasions. For example, net recipients would be required to reach out to other stakeholders to acquire new management information or breeding technologies, and hubs could facilitate the sharing of these resources throughout the network. Likewise, NGOs would be key partners to coordinate dissemination of plant material and management information, particularly in response to disasters affecting plant diseases (Etherton et al 2024). We also identified key gaps in these networks that can be addressed with strategic interventions. For example, policymakers could develop more communication pathways coming from stakeholders, in addition to those established with national research organizations. While farmer associations share plant material with other stakeholders (e.g., the public food sector and NGOs), their direct connections with international research may enhance varietal development, seed redistribution, and phytosanitary regulation. Further research efforts may include characterizing the frequency and type of these interactions and changes over time.

Perspectives on cropland connectivity. Our cropland connectivity analysis identified areas where wheat-specific pathogens or pests are likely to spread. High cropland connectivity is closely aligned with the geographic distribution of wheat production in Pakistan. For example, central Punjab and northern Sindh are part of major wheat-producing belts and are highly connected. The importance of these locations with high connectivity was supported by expert assessments of yield losses caused by established pests and diseases (Fig. 6b). Districts such as Hafizabad, Nankana Sahib, Multan, Lodhran, and western Bahawalpur have high cropland connectivity and high estimates of yield losses across diseases and pests. Districts such as Gujranwala, Faisalabad, Multan, and Sahiwal were identified as yield loss hotspots for rusts, aphids, and loose smut, and coincide with zones of high cropland connectivity. These findings are consistent with well-established observations that spatially homogenous host populations often facilitate the geographic spread of pests and pathogens (Stukenbrock and McDonald 2008)(Xing et al., 2020c).

Likewise, regions having moderate cropland connectivity, such as northern Sindh and parts of Khyber Pakhtunkhwa, correspond to wheat areas where experts reported moderate yield losses (Fig. 6b). These regions are spatially fragmented from homogeneous wheat production areas, so containment efforts might be more effective if outbreaks are detected early (Xing et al., 2020c; Zadoks et al., 1995) (Papaïx, 2011). Interestingly, Ghotki, Jacobabad, and Kashmore have low cropland connectivity, but expert assessments indicated that these districts have the highest cumulative yield losses. A possible explanation is that these regions serve as a structural bridge for pathogen/pest movement between wheat production areas in Punjab, Sindh, and Balochistan. Western Balochistan and the northern mountainous regions of Gilgit-Baltistan exhibited consistently low cropland connectivity, which is strongly coherent with mapping expert-elicited yield loss estimates. Isolated wheat landscapes combined with natural barriers are likely to reduce the movement of pests or pathogens in these regions (Batool et al., n.d.; Tuladhar et al., 2023; Xing et al., 2020c).

The spatial pattern in cropland connectivity also coincides with the geographic distribution of river basins in Pakistan, particularly along the Indus River (Gumma et al., 2019; Siddiqi et al., 2024b). This pattern highlights how interconnected landscapes along river systems can pose risks for the spread of pathogens or pests. Provinces having high cropland connectivity (central Punjab and northern Sindh) are also major hubs for seed and grain movement, both formal and informal. This scenario is likely to increase the chances of pathogens or pests moving across the wheat landscape if contaminated planting material reaches these trade hubs. Transboundary exchange of planting material across neighboring wheat regions (such as between Pakistan and India) is especially important for developing prevention strategies against invasive pathogens and pests.

- Transboundary exchange: Cross-border flows of both seed and grain, especially the informal exchanges between neighboring countries such as Iran and Afghanistan, underscore the permeability of borders.

Perspective on wheat blast introduction. In our global analysis, Pakistan poses a relatively low risk of introduction, given there is no direct international trade of wheat seed with countries where the pathogen is reported present (Argentina, Bangladesh, Bolivia, Brazil, and Zambia; Fig. 5). Pakistan had formally imported seed only from Mexico, Turkey, and Lebanon in the 2013-2022 period. In a global study, a simulation model estimated that wheat yield losses due to wheat blast are not likely in Pakistan based on current climate conditions (1980-2010) (Pequeno et al, 2024). However, more humid and warmer conditions (2040-2070) are projected to make some wheat production areas in Pakistan likely vulnerable to wheat blast infection (Pequeno et al 2024). Robust biosecurity efforts are active across the border between India and Bangladesh, following a recent incursion of wheat blast in this region (Das 2017).

Based on expert opinions, informal movement of wheat seed is possible from India to Pakistan (Fig. 3). If these patterns in informal trade allow seed transmission or wheat blast continue spreading gradually across the wheat landscape in India, the future risk of wheat blast occurrence would eventually increase for Pakistan. Wheat pests may enter a country, either naturally crossing contiguous wheat landscape at geopolitical borders, or introduced unintentionally via the international trade of high-risk commodities. This possible future risk posed by wheat blast in South Asia represents a new opportunity to coordinate preparedness strategies regionally and collectively. For example, farmers and extension agents should remain proactively vigilant for the potential appearance of disease symptoms suggestive of wheat blast (i.e., biosecurity surveillance). Pathogen exclusion for any species beyond the study here.

General perspective on wheat health. Safeguarding wheat health in Pakistan presents multifaceted challenges from diseases and pests, including informal seed systems, new genetic populations, and climate change. Our geographic analyses underscore the need for localized responses (e.g., farmer awareness) and large-scale interventions across stakeholders (e.g., greater collaboration with policymakers). Overall, these findings suggest that wheat health protection requires diversified investments in research, development, and capacity building as an adaptive strategy for national disease management. In the long term, this portfolio of investments can play a key role in improving the capacity to respond to established biological threats (Fig. 1) and in preventing future incursions of newly evolving, emerging, and invasive pathogens (Fig. 6). To tackle these challenges, effective management strategies for wheat health need greater integration of enhanced seed systems, (pro)active surveillance systems, and a larger management workforce.

For example, experts expressed that an integrated breeding improvement approach could focus on developing new wheat varieties that are high-yielding, nitrogen-use efficient (NUE), biofortified in zinc content, tolerant to drought and heat (i.e., resilient to climate change), resistant to diseases and insect pests, and adapted to specific agro-ecological zones in Pakistan. An emphasis should be placed on developing durable resistance to rust pathogens, given their major impacts nationally (Fig. 1) and increasing concerns about fungicide use. Likewise, a seed health plan requires an increased use of certified (ideally pathogen-free) seed of approved varieties, greater encouragement of seed treatment, traceability and testing, and modern facilities to save seed for next season.

For surveillance systems, epidemiological modeling tools could advise farmers or extension agents through forecasting systems for established diseases. More geographic disease risk analyses could support decision-making about proactive management of new, re-emerging, and invasive pathogens and pests. For example, high-connectivity, high-risk zones could be prioritized for disease monitoring and intervention. Preparedness for new threat incursions would benefit from enhanced identification systems (e.g., clinics with national databases for pathogen genomes and image-based diagnostics), early warning systems, and rapid response plans. Adapting these cutting-edge technologies will require increased coordination of national, international, and inter-institutional research systems.

Acknowledgements

We appreciate input from xxx experts who chose to remain anonymous and …. [List of names of other experts…]

Literature Cited

Afzal, A., Syed, S., Nawaz, H. H., Mustafa, R., Aziz, M., Khan, M., Khan, A., Javed, U., Rehman, A. U., Altaf, R., & Shakil, Q. (2024). Unraveling the Genetic and Geographic Diversity of Puccinia striiformis f. sp. Tritici (Pst) Populations for Effective Control of Stripe Rust in Global Wheat Production. *Pakistan Journal of Agricultural Research*, *37*(2), 88–101. https://doi.org/10.17582/JOURNAL.PJAR/2024/37.2.88.101

Akhter, R., & Mirza, S. N. (2006). Arid steppes of Balochistan (Pakistan). *Science et Changements Planétaires / Sécheresse*, *17*(1), 203–209. https://www.jle.com/fr/revues/sec/e-docs/arid_steppes_of_balochistan_pakistan__270100/article.phtml?tab=texte

Ali, S. S. (2013). Changing Spatial Patterns of Agriculture in the Punjab Province and the Food Sustainability. *Journal of Basic & Applied Sciences*, *9*(9), 389–400. https://doi.org/10.6000/1927-5129.2013.09.50

Arshad, I., Rasul, A., Hussain, S. I., Aslam, H. M. U., Hayat, K., Hassan, M. N. U., Muqeet, S., , Amina, Umar, Y., Nasir, S., Tehseen, A., Arshad, I., Rasul, A., Hussain, S. I., Aslam, H. M. U., Hayat, K., Hassan, M. N. U., Muqeet, S., … Tehseen, A. (2019). Impact of Climate Change on Epidemiology of Various Pests of Wheat Crop in Punjab Pakistan. *American Journal of Plant Sciences*, *10*(1), 236–247. https://doi.org/10.4236/AJPS.2019.101018

Authority, E. F. S. (2014). Guidance on expert knowledge elicitation in food and feed safety risk assessment. *EFSA Journal*, *12*(6), 3734.

Awais, M., Zhao, J., Cheng, X., Ghaffar Khoso, A., Ju, M., Ur Rehman, Z., Iqbal, A., Rameez Khan, M., Chen, W., Liu, M., Ma, X., Wang, L., Liu, W., Du, Z., Sun, M., Zhang, G., Kang, Z., & Ali, S. (2023). Himalayan mountains imposing a barrier on gene flow of wheat yellow rust pathogen in the bordering regions of Pakistan and China. *Fungal Genetics and Biology*, *164*, 103753. https://doi.org/10.1016/J.FGB.2022.103753

Bahri, B., Shah, S. J. A., Hussain, S., Leconte, M., Enjalbert, J., & de Vallavieille-Pope, C. (2011). Genetic diversity of the wheat yellow rust population in Pakistan and its relationship with host resistance. *Plant Pathology*, *60*(4), 649–660. https://doi.org/10.1111/J.1365-3059.2010.02420.X;JOURNAL:JOURNAL:13653059;PAGE:STRING:ARTICLE/CHAPTER

Barry, S. C., Caley, P., Liu, S., Paini, D. R., Carey, G., & Clark, J. (2015). Development of an Expert Based Model for Improved Biofouling Risk Assessment. *CEBRA Project A*, *1402*.

Batool, S., Khan, T., Karim, R., Zafar, M., & Ahmed, S. (n.d.). Climate Change and Agricultural Transformation in Shigar Valley, Gilgit-Baltistan, Pakistan: A Commune-Scientific Perception. *International Journal of Environment, Agriculture and Biotechnology (IJEAB)*, *1*(4). https://doi.org/10.22161/ijeab/1.4.39

Bhatta, M., Morgounov, A., Belamkar, V., Wegulo, S. N., Dababat, A. A., Erginbas-Orakci, G., Bouhssini, M. El, Gautam, P., Poland, J., Akci, N., Demir, L., Wanyera, R., & Baenziger, P. S. (2019). Genome-Wide Association Study for Multiple Biotic Stress Resistance in Synthetic Hexaploid Wheat. *International Journal of Molecular Sciences 2019, Vol. 20, Page 3667*, *20*(15), 3667. https://doi.org/10.3390/IJMS20153667

Bishaw, Z., & Turner, M. (2008). Linking participatory plant breeding to the seed supply system. *Euphytica*, *163*(1), 31–44. https://doi.org/10.1007/S10681-007-9572-6/FIGURES/4

Borlaug, N. E. (2004). International Agricultural Research. *Science*, *303*(5661), 1137–1138. https://doi.org/10.1126/SCIENCE.303.5661.1137

Buddenhagen, C. E., Rubenstein, J. M., Hampton, J. G., & Philip Rolston, M. (2021). The phytosanitary risks posed by seeds for sowing trade networks. *PLOS ONE*, *16*(11), e0259912. https://doi.org/10.1371/JOURNAL.PONE.0259912

Chapter 14: The importance of seed circulation networks in the resilience of seed systems in: A Research Agenda for Social Networks and Social Resilience. (n.d.). Retrieved April 26, 2025, from https://www.elgaronline.com/edcollchap/book/9781803925783/book-part-9781803925783-19.xml

Chen, W., & Zhang, H. (2022). Characterizing the Structural Evolution of Cereal Trade Networks in the Belt and Road Regions: A Network Analysis Approach. *Foods 2022, Vol. 11, Page 1468*, *11*(10), 1468. https://doi.org/10.3390/FOODS11101468

Chen, X., Wang, Y., Chen, Y., Fu, S., & Zhou, N. (2023). NDVI-Based Assessment of Land Degradation Trends in Balochistan, Pakistan, and Analysis of the Drivers. *Remote Sensing 2023, Vol. 15, Page 2388*, *15*(9), 2388. https://doi.org/10.3390/RS15092388

Etherton, B. A., Plex Sulá, A. I., Mouafo-Tchinda, R. A., Kakuhenzire, R., Kassaye, H. A., Asfaw, F., Kosmakos, V. S., McCoy, R. W., Xing, Y., Yao, J., Sharma, K., & Garrett, K. A. (2025). Translating Ethiopian potato seed networks: Identifying strategic intervention points for managing bacterial wilt and other diseases. *Agricultural Systems*, *222*, 104167. https://doi.org/10.1016/J.AGSY.2024.104167

Faheem, M., Saeed, S., Sajjad, A., Wang, S., & Ali, A. (2019). Spatio-temporal variations in wheat aphid populations and their natural enemies in four agro-ecological zones of Pakistan. *PLOS ONE*, *14*(9), e0222635. https://doi.org/10.1371/JOURNAL.PONE.0222635

Fayyaz, M., Rattu, A., Ahmad, I., & Mujeeb-Kazi, A. (2008). *CURRENT STATUS OF THE OCCURRENCE AND DISTRIBUTION OF (PUCCINIA TRITICINA) WHEAT LEAF RUST VIRULENCE IN PAKISTAN*.

Frisvold, G. B., & Reeves, J. M. (2014). Herbicide Resistant Crops and Weeds: Implications for Herbicide Use and Weed Management. *Integrated Pest Management: Pesticide Problems, Vol.3*, 331–354. https://doi.org/10.1007/978-94-007-7796-5_14

Gent, D. H., Bhattacharyya, S., & Ruiz, T. (2019). Prediction of spread and regional development of hop powdery mildew: A network analysis. *Phytopathology*, *109*(8), 1392–1403. https://doi.org/10.1094/PHYTO-12-18-0483-R/ASSET/IMAGES/LARGE/PHYTO-12-18-0483-R_F4-1563334526660.JPEG

Ghulam Murtaza Safi, Muhammad Sohail Gadiwala, Farkhunda Burke, Muhammad Azam, & Muhammad Fahad Baqa. (2014). Agricultural Productivity in Balochistan Province of Pakistan A Geographical Analysis. *Journal of Basic & Applied Sciences*, *10*, 292–298. https://doi.org/10.6000/1927-5129.2014.10.38)

Gumma, M. K., Thenkabail, P. S., Teluguntla, P., & Whitbread, A. M. (2019). Indo-Ganges River Basin Land Use/Land Cover (LULC) and Irrigated Area Mapping. *Indus River Basin: Water Security and Sustainability*, 203–228. https://doi.org/10.1016/B978-0-12-812782-7.00010-2

Gunduz, O., Ceyhan, V., Aslan, A., & Bayramoglu, Z. (2016). Determinants of farmers' risk aversion in apricot production in turkey. *Int. J. Manag. Appl. Sci*, *2*, 149–155.

Gustafson, L. L., Gustafson, D. H., Antognoli, M. C., & Remmenga, M. D. (2013). Integrating expert judgment in veterinary epidemiology: Example guidance for disease freedom surveillance. *Preventive Veterinary Medicine*, *109*(1–2), 1–9.

Helicke, N. A. (2015). Seed exchange networks and food system resilience in the United States. *Journal of Environmental Studies and Sciences*, *5*(4), 636–649. https://doi.org/10.1007/S13412-015-0346-5/METRICS

Hellin, J., & Camacho, C. (2017). Agricultural research organisations' role in the emergence of agricultural innovation systems. *Development in Practice*, *27*(1), 111–115. https://doi.org/10.1080/09614524.2017.1256373;REQUESTEDJOURNAL:JOURNAL:CDIP20;WGROUP:STRING:PUBLICATION

Hemming, V., Burgman, M. A., Hanea, A. M., McBride, M. F., & Wintle, B. C. (2018). A practical guide to structured expert elicitation using the IDEA protocol. *Methods in Ecology and Evolution*, *9*(1), 169–180.

Hemming, V., Walshe, T. V, Hanea, A. M., Fidler, F., & Burgman, M. A. (2018). Eliciting improved quantitative judgements using the IDEA protocol: A case study in natural resource management. *PloS One*, *13*(6), e0198468.

Hester, S. M., & Cacho, O. J. (2017). The contribution of passive surveillance to invasive species management. *Biological Invasions*, *19*, 737–748.

Hoffmann, S., Fischbeck, P., Krupnick, A., & McWilliams, M. (2007). Using expert elicitation to link foodborne illnesses in the United States to foods. *Journal of Food Protection*, *70*(5), 1220–1229.

Hughes, G., & Madden, L. V. (2002). Some methods for eliciting expert knowledge of plant disease epidemics and their application in cluster sampling for disease incidence. *Crop Protection*, *21*(3), 203–215.

Hussain, Intizar., Marikar, Fuard., & Jehangir, W. Ahmed. (2000). *Productivity and performance of irrigated wheat farms across canal commands in the Lower Indus Basin*. 28.

Islam, M. T. (2016). Magnaporthe oryzae Triticum pathotype (wheat blast). *CABI Compendium*. https://doi.org/10.1079/CABICOMPENDIUM.121970

Islam, M. T., Croll, D., Gladieux, P., Soanes, D. M., Persoons, A., Bhattacharjee, P., Hossain, M. S., Gupta, D. R., Rahman, M. M., Mahboob, M. G., Cook, N., Salam, M. U., Surovy, M. Z., Sancho, V. B., Maciel, J. L. N., NhaniJúnior, A., Castroagudín, V. L., Reges, J. T. de A., Ceresini, P. C., … Kamoun, S. (2016). Emergence of wheat blast in Bangladesh was caused by a South American lineage of Magnaporthe oryzae. *BMC Biology*, *14*(1), 1–11. https://doi.org/10.1186/S12915-016-0309-7/FIGURES/5

Jonathan, F. T., & Mahendranathan, C. (2024). Impact of Climate Change on Plant Diseases. *AGRIEAST: Journal of Agricultural Sciences*, *18*(2), 1–17. https://doi.org/10.4038/AGRIEAST.V18I2.133

Kaur, G., Singh, H., Maurya, S., Kumar, C., & Kumar, A. (2023). Current scenario of climate change and its impact on plant diseases. *Plant Science Today*, *10*(4), 163–171. https://doi.org/10.14719/PST.2479

Khan, M. R., Imtiaz, M., Farhatullah, Ahmad, S., & Ali, S. (2019). Northern Himalayan region of Pakistan with cold and wet climate favors a high prevalence of wheat powdery mildew. *Sarhad Journal of Agriculture*, *35*(1), 187–193. https://doi.org/10.17582/JOURNAL.SJA/2019/35.1.187.193

Khan, M. R., Imtiaz, M., Munir, I., Hussain, I., & Ali, S. (2021). Differential distribution of leaf rust across major wheat growing regions of pakistan revealed through a three year surveillance effort. *Pakistan Journal of Botany*, *53*(1), 261–266. https://doi.org/10.30848/PJB2021-1(21)

KHANFRI, S., BOULIF, M., & LAHLALI, R. (2018). Yellow Rust (Puccinia striiformis): a Serious Threat to Wheat Production Worldwide. *Notulae Scientia Biologicae*, *10*(3), 410–423. https://doi.org/10.15835/NSB10310287

Kuhlmann, K., & Dey, B. (2021). Using Regulatory Flexibility to Address Market Informality in Seed Systems: A Global Study. *Agronomy 2021, Vol. 11, Page 377*, *11*(2), 377. https://doi.org/10.3390/AGRONOMY11020377

Lahlali, R., Taoussi, M., Laasli, S. E., Gachara, G., Ezzouggari, R., Belabess, Z., Aberkani, K., Assouguem, A., Meddich, A., El Jarroudi, M., & Barka, E. A. (2024). Effects of climate change on plant pathogens and host-pathogen interactions. *Crop and Environment*, *3*(3), 159–170. https://doi.org/10.1016/J.CROPE.2024.05.003

Maciel, J. L. N., Ceresini, P. C., Castroagudin, V. L., Zala, M., Kema, G. H. J., & McDonald, B. A. (2014). Population structure and pathotype diversity of the wheat blast pathogen magnaporthe oryzae 25 years after its emergence in Brazil. *Phytopathology*, *104*(1), 95–107. https://doi.org/10.1094/PHYTO-11-12-0294-R;CTYPE:STRING:JOURNAL

McEwan, M. A., Almekinders, C. J. M., Andrade-Piedra, J. J. L., Delaquis, E., Garrett, K. A., Kumar, L., Mayanja, S., Omondi, B. A., Rajendran, S., & Thiele, G. (2021). "Breaking through the 40% adoption ceiling: Mind the seed system gaps." A perspective on seed systems research for development in One CGIAR. *Outlook on Agriculture*, *50*(1), 5–12. https://doi.org/10.1177/0030727021989346;WGROUP:STRING:PUBLICATION

Montenegro, M. (2018). *Title Breeding Grounds for Biodiversity Renewing Crop Genetic Resources in an Age of Industrial Food*. https://escholarship.org/uc/item/2x88f3j7

Moreddu, C., & Poppe, K. J. (2013). Agricultural Research and Innovation Systems in TransitionLes systèmes de recherche et d'innovation agricoles en transitionAgrarforschung und Innovationssysteme im Wandel. *EuroChoices*, *12*(1), 15–20. https://doi.org/10.1111/1746-692X.12014

Muijs, D., Ainscow, M., Chapman, C., & West, M. (2011). Networking and Collaboration as a Public Policy Framework. *Collaboration and Networking in Education*, 9–17. https://doi.org/10.1007/978-94-007-0283-7_2

Mushtaq, K., Abbas, F., & Ghafoor, A. (2006). TESTING THE LAW OF ONE PRICE: RICE MARKET INTEGRATION IN PUNJAB, PAKISTAN. In *J Agri. Sci* (Vol. 43).

New dissemination strategies and emerging figures: the innovation broker | Agriregionieuropa. (n.d.). Retrieved April 27, 2025, from https://agriregionieuropa.univpm.it/it/content/article/31/28/nuove-strategie-di-disseminazione-e-figure-emergenti-linnovation-broker

Papaïx, J. (2011). *Structure of agricultural landscapes and epidemic risk, a demo-genetic approach.* https://doi.org/10.34894/VQ1DJA

Pink, D. A. C., & Hand, P. (2002). Plant resistance and strategies for breeding resistant varieties. *Https://Pps.Agriculturejournals.Cz/Doi/10.17221/10310-PPS.Html*, *38*(SI 1-6th Conf EFPP), S9–S14. https://doi.org/10.17221/10310-PPS

Plex Sulá, A. I., Batuman, O., Cellier, G., Dufault, N. S., Etherton, B. A., Lowe-Power, T. M., McVay, J. D., Paret, M., Penca, C., Schroeder, K., Suder, P., Takeuchi, Y., Tonnang, H., Wang, Y., & Garrett, K. A. (n.d.). An integrated risk assessment framework for proactive global. *International Centre of Insect Physiology and Ecology*, *12*(4).

Potter, K., & Oloyede, J. O. (2023). *The Impact of Climate Change on Plant Pathogens*. https://doi.org/10.31219/OSF.IO/E4XKZ

Rai, S., Kumar, A., Singh, I. K., & Singh, A. (2020). Seedborne Diseases and Its Management. *Advances in Seed Production and Management*, 611–626. https://doi.org/10.1007/978-981-15-4198-8_31

Raj, S., Brinkley, C., & Ulimwengu, J. (2022). Connected and extracted: Understanding how centrality in the global wheat supply chain affects global hunger using a network approach. *PLOS ONE*, *17*(6), e0269891. https://doi.org/10.1371/JOURNAL.PONE.0269891

Ramaswami, R., Ravi, S., & Chopra, S. (2008). Risk management in agriculture. *Discussion Papers*, *03–08*, 3–8.

Ranaivoson, L., Naudin, K., Ripoche, A., Rabeharisoa, L., & Corbeels, M. (2019). Effectiveness of conservation agriculture in increasing crop productivity in low-input rainfed rice cropping systems under humid subtropical climate. *Field Crops Research*, *239*, 104–113.

Rattu, A.-U.-R., Asad, S., Fayyaz, M., Zakria, M., & Ahmad, Y. (2011). *Status of foliar diseases of wheat in Punjab, Pakistan*. *9*(1), 39–42.

Riwthong, S., Schreinemachers, P., Grovermann, C., & Berger, T. (2017). Agricultural commercialization: Risk perceptions, risk management and the role of pesticides in Thailand. *Kasetsart Journal of Social Sciences*, *38*(3), 264–272.

Sakr, N., Kurdali, F., Attar, J., & Ammar, S. (2024). First Evidence of Increased Fusarium Head Blight Symptoms in Durum Wheat Subjected to Post-Flowering Moisture. *Pakistan Journal of Phytopathology*, *36*(2), 467–478. https://doi.org/10.33866/PHYTOPATHOL.036.02.1152

Shafi, U., Mumtaz, R., Haq, I. U., Hafeez, M., Iqbal, N., Shaukat, A., Zaidi, S. M. H., & Mahmood, Z. (2021). Wheat Yellow Rust Disease Infection Type Classification Using Texture Features. *Sensors 2022, Vol. 22, Page 146*, *22*(1), 146. https://doi.org/10.3390/S22010146

Shannon, H. D., & Motha, R. P. (2015). Managing weather and climate risks to agriculture in North America, Central America and the Caribbean. *Weather and Climate Extremes*, *10*, 50–56.

Shujaat, N., Sajid, M., Khan, F. U., & Nawaz, I. (2025). Assessment of fungal diseases and their impact on yield in wheat varieties under fungicide treatment. *Plant Protection*, *9*(1), 57–68. https://doi.org/10.33804/PP.009.01.5549

Siddig, K., Stepanyan, D., Wiebelt, M., Grethe, H., & Zhu, T. (2020). Climate change and agriculture in the Sudan: Impact pathways beyond changes in mean rainfall and temperature. *Ecological Economics*, *169*, 106566.

Siddiqi, A., Wescoat, J. L., & Selin, N. E. (2024a). Evolution of system connectivity to support food production in the Indus Basin in Pakistan. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(18), e2215682121. https://doi.org/10.1073/PNAS.2215682121/SUPPL_FILE/PNAS.2215682121.SAPP.PDF

Siddiqi, A., Wescoat, J. L., & Selin, N. E. (2024b). Evolution of system connectivity to support food production in the Indus Basin in Pakistan. *Proceedings of the National Academy of Sciences of the United States of America*, *121*(18), e2215682121. https://doi.org/10.1073/PNAS.2215682121/SUPPL_FILE/PNAS.2215682121.SAPP.PDF

Siyal, A. W., Gerbens-Leenes, W., Aldaya, M. M., & Naz, R. (2023). The importance of irrigation supply chains within the water footprint: an example from the Pakistani part of the Indus basin. *Journal of Integrative Environmental Sciences*, *20*(1). https://doi.org/10.1080/1943815X.2023.2208644;WGROUP:STRING:PUBLICATION

Smolenaars, W. J., Sommerauer, W. J. W., van der Bolt, B., Jamil, M. K., Dhaubanjar, S., Lutz, A., Immerzeel, W., Ludwig, F., & Biemans, H. (2023). Spatial adaptation pathways to reconcile future water and food security in the Indus River basin. *Communications Earth and Environment*, *4*(1), 1–12. https://doi.org/10.1038/S43247-023-01070-3;SUBJMETA=106,2786,694,704,841,844;KWRD=CLIMATE-CHANGE+ADAPTATION,PROJECTION+AND+PREDICTION

Soomoro, S., Samoo, M. S., Jamali, A. R., & Channa, G. S. (2024). Assessing leaf rust resistance in Pakistani wheat landraces and its impact on grain yield. *Plant Protection*, *8*(2), 269–274. https://doi.org/10.33804/PP.008.02.5117

Sufyan, M., Iqbal Mirza, J., Saeed, M., Fayyaz, M., Ahmad Khanzada, K., ur Rehman Rattu, A., & Qasim Kakar, M. (2021). Yellow rust races found in 2018-19 collection from wheat growing areas of Pakistan. *Pure and Applied Biology*, *10*(4), 1063–1069. https://doi.org/10.19045/bspab.2021.100110

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

Tonapi, V. A., Ravinder Reddy, C., Prasad, S. R., Tomar, B. S., Singh, S., Pandey, S., Natarajan, S., & Lal, S. K. (2012). *Strategies to Build Viable Community Seed System in Dry land Ecosystems for Sustainable Seed and Food Security in India*.

Tu, Y., Shu, Z., Wu, W., He, Z., & Li, J. (2024). Spatiotemporal analysis of global grain trade multilayer networks considering topological clustering. *Transactions in GIS*, *28*(3), 509–534. https://doi.org/10.1111/TGIS.13149

Tuladhar, S., Hussain, A., Baig, S., Ali, A., Soheb, M., Angchuk, T., Dimri, A. P., & Shrestha, A. B. (2023). Climate change, water and agriculture linkages in the upper Indus basin: A field study from Gilgit-Baltistan and Leh-Ladakh. *Frontiers in Sustainable Food Systems*, *6*, 1012363. https://doi.org/10.3389/FSUFS.2022.1012363/BIBTEX

Uddin, S., Iqbal, J., Abbasi, B. A., Ijaz, S., Murtaza, G., Waseem, M., Quraishi, U. M., Adiba, A., Aljowaie, R. M., Almutairi, S. M., & Iqbal, R. (2024). Unveiling the genetic diversity and host specificities of rust: morphological and molecular characterization of Berberis species. *Genetic Resources and Crop Evolution*, *72*(3), 3123–3137. https://doi.org/10.1007/S10722-024-02156-3/METRICS

Ullah, A., Nawaz, A., Farooq, M., & Siddique, K. H. M. (2021). Agricultural Innovation and Sustainable Development: A Case Study of Rice–Wheat Cropping Systems in South Asia. *Sustainability 2021, Vol. 13, Page 1965*, *13*(4), 1965. https://doi.org/10.3390/SU13041965

Ullah, R., Shivakoti, G. P., & Ali, G. (2015). Factors effecting farmers' risk attitude and risk perceptions: The case of Khyber Pakhtunkhwa, Pakistan. *International Journal of Disaster Risk Reduction*, *13*, 151–157. https://doi.org/https://doi.org/10.1016/j.ijdrr.2015.05.005

Wang, Y. (2017). Estimation of Yield Losses due to Leaf Rust and Late W*®Seeding on Wheat (Triticum aestivum L) Variety Seher-06 in District Faisalabad, Punjab, Pakistan. *Advances in Biotechnology & Microbiology*, *5*(2). https://doi.org/10.19080/AIBM.2017.05.555657

Warnke, P., Koschatzky, K., Dönitz, E., Zenker, A., Stahlecker, T., Som, O., Cuhls, K., & Güth, S. (2016). Opening up the innovation system framework towards new actors and institutions. *Discussion Papers "Innovation Systems and Policy Analysis."* https://doi.org/10.24406/PUBLICA-FHG-297722

Whittle, P., Jarrad, F., & Mengersen, K. (2013). Design of the quarantine surveillance for non-indigenous species of invertebrates on Barrow Island. *Records of the Western Australian Museum, Supplement*, *83*, 113–130.

Wittmann, M. E., Cooke, R. M., Rothlisberger, J. D., Rutherford, E. S., Zhang, H., Mason, D. M., & Lodge, D. M. (2015). Use of structured expert judgment to forecast invasions by bighead and silver carp in Lake Erie. *Conservation Biology*, *29*(1), 187–197.

Woo, D. K., Riley, W. J., & Wu, Y. (2020). More fertilizer and impoverished roots required for improving wheat yields and profits under climate change. *Field Crops Research*, *249*, 107756.

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. (2020a). 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

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. (2020b). 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

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. (2020c). 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

Xu, T. (2025). Grain Trade: A Literature Review and Research Outlook. *Review of Economic Assessment*, *3*(4), 1–14. https://doi.org/10.58567/REA03040001

Yin, Z., Hu, J., Zhang, J., Zhou, X., Li, L., & Wu, J. (2024). Temporal and spatial evolution of global major grain trade patterns. *Journal of Integrative Agriculture*, *23*(3), 1075–1086. https://doi.org/10.1016/J.JIA.2023.10.032

Zadoks, J. C., Anderson, P. K., & Savary, S. (1995). *An eco-regional perspective of crop protection problems*. 437–452. https://doi.org/10.1007/978-94-011-0121-9_22

Zahid, M. S., Qayyum, A., & Malik, W. S. (2007). Dynamics of Wheat Market Integration in Northern Punjab, Pakistan. *The Pakistan Development Review*, *46*(4), 817–830. https://doi.org/10.30541/V46I4IIPP.817-830

Zhu, S., Gong, S., Zhu, S., & Gong, S. (2023). Research on Weighted Directed Dynamic Multiplexing Network of World Grain Trade Based on Improved MLP Framework. *Journal of Computer and Communications*, *11*(7), 191–207. https://doi.org/10.4236/JCC.2023.117012

Zorn, M., Hrvatin, M., & Perko, D. (2020). Hydrological connectivity: an introduction to the concept // Hidrološka povezljivost – temeljni konceptualni okvir. *Geografski Vestnik*, *92*(1), 37-51–37–51. https://doi.org/10.3986/GV92102