A nationwide assessment of wheat diseases and pests in Pakistan

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ABSTRACT

Wheat production in Pakistan faces persistent threats from diseases and pests. However, limited geographic information exists on their local risks, economic impacts, and management practices. We conducted an expert knowledge elicitation to provide the first integrated assessment of wheat health in Pakistan. Experts mapped yield losses for major diseases and pests at the district level. We used network analysis to characterize seed and grain exchange and stakeholder interactions. Analysis of wheat cropland connectivity identified locations that are likely to play important epidemiological roles. Cumulative yield losses ranged from 4% to 16%, with hotspots in central Punjab and northern Sindh.

Stripe rust, leaf rust, and aphids remain top threats, with climate change and pathogen subpopulations identified as primary drivers of yield losses. Informal exchange of wheat seed (70-75%) and grain (68-97%) was common in national trade networks, highlighting a key pathway for potential spread of seedborne pathogens. Stakeholder networks indicated that farmer associations and seed dealers are strategic points for both information sharing and seed health monitoring. Cropland connectivity analysis identified a highly connected wheat landscape along the Indus River, overlapping with national disease hotspots and facilitating pathogen proliferation. Pakistan has a moderate potential for wheat blast introduction, yet climate change and informal seed movement could increase this vulnerability. These findings provide farmers, researchers, and policymakers with actionable control points to enhance wheat health systems in Pakistan. This study established a rapid information baseline in support of geographically targeted surveillance, coordinated seed system interventions, and epidemic preparedness planning.

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 about 24% to gross domestic product (GDP) and employed 37.4% of the national workforce (Government of Pakistan, 2018). Cultivation of wheat in Pakistan spans over 9.2 million hectares, or around 40% of the total cropped area, with an average yield of 2.7 tonnes per hectare (Ali et al., 2017; Shaukat et al., 2023). However, 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 biotic 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, causing consistent annual yield losses. Stem rust (*P. graminis* f. sp. *tritici*), though globally significant, remains sporadic in Pakistan and is mostly reported in coastal Sindh (Iqbal et al., 2010; Rehman et al., 2019).

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 trade risks due to its quarantine status (Aasma et al., 2019). Loose smut, spot blotch, and Fusarium head blight occur sporadically but can degrade grain quality (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 such as the cereal yellow dwarf virus (Wains et al., 2014). Other pests such as cereal leaf beetles and termites are considered minor but locally important. Recent unpublished surveys (2022–2025) indicate that national disease dynamics are influenced by weather, varieties, 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 remain under-monitored yet highly damaging.

National response and surveillance gaps

Pakistan has implemented phytosanitary measures through the Department of Plant Protection (DPP), including pest risk analyses (PRAs) for wheat imports, heat or fumigation treatment of high-risk consignments, and phytosanitary certificates in line with International Plant Protection Convention (IPPC) standards. DPP operates under the Ministry of National Food Security and Research (MNFSR) and is formally designated as Pakistan's National Plant Protection Organization (NPPO) under IPPC, with legal authority grounded in the Plant Quarantine Act (1976) and Plant Quarantine Rules (2019) (Government of Pakistan, 2019; IPPC, 2016). Recent actions have also targeted seedborne quarantine pathogens such as *T. indica* (Karnal bunt), with stricter import protocols and enhanced surveillance following regional outbreaks (Tribune, 2024).

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), but a geographically resolved national assessment is lacking. In practice, passive surveillance conducted by agricultural officers or farmers is the primary source of pest and disease data, with only occasional targeted inspections. These approaches miss broader spatial patterns of pathogen and pest distributions. Rust surveillance is relatively advanced in Pakistan, supported by national initiatives and international collaborations with global programs like the Borlaug Global Rust Initiative (BGRI) and CIMMYT. Pakistan also collaborates with CABI to support early warning systems, particularly for rusts and invasive pests (CABI, 2023). In contrast, a surveillance system for non-rust diseases and pests remains underdeveloped, leading to delayed detection and limited response to emerging threats.

Nationwide pest and disease surveillance in Pakistan remains challenging due to financial and logistical constraints (Gustafson et al., 2013), resulting in fragmented information for strategic decision-making. To address this constraint, expert knowledge elicitation offers a reproducible, structured, and cost-effective alternative to generating actionable evidence (Robledo et al 2025). By systematically drawing on the experience of specialists, expert elicitation can capture historical impacts, characterize current disease pressures, and anticipate emerging risks (Robledo et al 2025). This approach bridges surveillance gaps, guides geographic prioritization of interventions, and complements limited objective datasets (Authority, 2014; Hoffmann et al., 2007; Hemming, Burgman, et al., 2018; Hemming, Walshe, et al., 2018; Whittle et al., 2013). Expert elicitation has proven effective across diverse domains, from invasive species management to national-scale plant disease risk modeling (Barryf et al., 2015; Wittmann et al., 2015; Hughes & Madden, 2002; Thomas-Sharma et al., 2017) and offers a timely opportunity to strengthen epidemiological insights for Pakistan's wheat sector.

Complementing expert knowledge, geospatial network analysis offers another critical dimension for understanding plant health (Etherton et al, 2023, 2025). Pathogen and pest distributions are shaped not only by climate and host availability, but also by human-mediated dispersal through seed exchange, equipment movement, and the mobility of people across farming regions (Gunduz et al., 2016; Gent et al., 2019). Incorporating network analysis into geographic risk assessments allows for more realistic evaluations of spread pathways and helps pinpoint strategic intervention points. This approach has been 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). Applying it to wheat in Pakistan aligns with national biosecurity priorities, offering an evidence-based approach to guide NPPO surveillance, seed certification policies, and regional preparedness against transboundary threats such as wheat blast.

This study leverages expert knowledge elicitation and spatial network analysis to improve understanding of large-scale epidemiological risks in Pakistan's wheat production system. Specifically, we aim to:

- Map the spatial patterns of crop yield losses associated with 34 known wheat diseases and pests at the district level, providing the first comprehensive national perspective on their impacts.
- Synthesize expert perspectives on implemented management practices, highlighting strengths, weaknesses, and gaps in control strategies.
- Evaluate the potential for local spread of emerging or re-emerging threats by applying cropland connectivity analysis, understanding potential epidemic pathways across production zones.
- Assess the potential for (re)introduction of wheat pathogens through international trade and the domestic movement of seed and grain, identifying critical nodes of vulnerability in the wheat supply chain.

Together, these objectives provide an evidence-based framework to guide national surveillance, preparedness, and targeted management interventions, supporting Pakistan's broader goals of food security, agricultural sustainability, and economic resilience.

MATERIALS AND METHODS

Study Area. This study focused on Pakistan's major wheat-producing regions to ensure broad geographic representation of the crop's production landscape and associated pest and disease pressures. Wheat was selected due to its central role in national food security and widespread cultivation.

To capture spatial variability in the expert knowledge elicitation, experts were invited from wheat-growing districts across all four provinces. The core wheat belt, comprising central and southern Punjab and parts of upper Sindh, was prioritized due to its high production volume. Punjab contributes approximately 75% of national wheat output, while Sindh accounts for about 11–12%, mostly from canal-irrigated regions. Additional data was incorporated from key irrigated zones in Khyber Pakhtunkhwa (KPK) and selected areas of Balochistan, ensuring ecological and regional coverage. This spatial framework underpinned the implementation of expert knowledge elicitation and subsequent mapping of wheat pest and disease risks.

Expert knowledge elicitation. We structured the expert knowledge elicitation in three stages, adapted from established methodologies applied in plant health risk assessments (Robledo et al 2025; Anderson et al., 2021).

Stage 1: Expert Selection and Instrument Preparation. To ensure comprehensive and regionally informed input, a structured nomination and review process was conducted prior to the expert knowledge elicitation 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 nominated experts with backgrounds in pathology, entomology, agronomy, plant breeding, and related disciplines. Nominations were assessed by a four-member panel to ensure relevant expertise based on a review of the experts' CVs. Priority was given to individuals with extensive research or applied experience across the wheat value chain.

From a short list of 25 candidates, 23 experts participated in the in-person workshop. The spatial representation of participating experts matched national production patterns, with more experts representing main wheat-producing areas (Punjab and Sindh). Contributing institutions are listed in Supplementary Data 1.

The formal first stage of the EKE began with defining its scope and structure. This process was led by a core organizing team of national wheat specialists and facilitators, distinct from expert participants, to avoid bias in framing. This team ensured that the elicitation process remained aligned with national wheat health priorities and responsive to Pakistan's production systems.

Through a series of planning meetings, the team compiled a comprehensive list of target threats. These included eight high-impact diseases and pests causing major on-field losses, 26 additional species responsible for minor but recurring damage, and seven post-harvest pathogens and pests (need to refer instrument or whichever doc has that detailed list). We also identified the types of geographic information that would provide a broad yet actionable perspective of the national wheat crop health and that could be reliably and efficiently elicited through expert knowledge. The expert knowledge elicitation was therefore designed to capture data on the local impact, potential spread, and available management options for wheat diseases and pests.

Structure and Content of the Elicitation Instrument. Based on this prioritization of target threats and geographic determinants, we developed a structured elicitation instrument, comprising seven thematic sections to systematically capture expert input (Supplementary Material 1). Each section targeted a distinct dimension of wheat health, ensuring systematic coverage of epidemiological and management aspects across Pakistan's wheat production zones. These sections can be divided as follows.

1. **High-priority threats.** Experts provided estimates of yield losses, and influence of climate change and agronomic practices for eight key diseases and pests.
2. **Additional threats.** Experts rated yield losses caused by 26 minor but nationally or provincially relevant diseases and pests, including post-harvest pests.
3. **Stakeholder interactions.** Experts estimated whether exchange of planting materials and information occurred among policy, research, industry, and farmer groups (Garrett, 2021).
4. **Seed and grain exchange routes.** Experts evaluated whether formal or informal flows existed across provinces and with neighboring countries, to understand potential dispersal pathways of seedborne pests.
5. **Seed and crop management practices.** Experts estimated patterns in certified seed use, varietal diversity, and pesticide application practices across different production areas.
6. **Future outlook.** Experts provided perspectives on wheat health challenges and opportunities over a 5- and 20-year period.
7. **Process evaluation.** Participants provided feedback on the elicitation instrument and workshop.

To strengthen interpretation, the instrument also included seven closed-ended questions, capturing the spatial and thematic experience of each participant. We used the number of years of experience in a specific region or topic as a proxy for expert confidence.

Stage 2: Elicitation 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 elicitation methodology, and examples from similar elicitation applications. Facilitators then introduced the elicitation instrument and clarified questions. For each question, experts then completed the instrument in a stepwise process. (i) Individual assessment: Each participant provided independent answers to a question. (ii) Small-group discussion: Participants were then divided into teams of 4-6 to compare responses and provide a collective answer for a specific question. (iii) Plenary dialogue: Group responses were presented to all participants, followed by discussion to resolve discrepancies and potentially reach consensus.

This participatory approach encouraged debate, highlighted regional differences in perspective, and promoted more robust outcomes. Each expert or leader of a small team manually documented their answers on a hard copy of the elicitation instrument. For questions addressing spatial patterns, experts annotate district maps of Pakistan, coloring each district according to predefined scales. We then digitized all responses in a tabular form (Data S1).

Stage 3: Data analysis of expert knowledge. Although expert elicitation may creates variations in expert opinions and lacks the precision of objective measurement, it provides a rapid, cost-effective, and nationally representative assessment of epidemic and pest risk factors, particularly in low-income settings where empirical surveillance is limited (Robledo et al 2025). The expert elicitation in Pakistan met these criteria, drawing on sufficient numbers of domain experts across major production zones.

1. **Quantitative analysis.** For closed-ended questions, we analyzed individual responses separately from the collective responses generated by small expert groups. Since these two types of responses represent ordinal data, we calculated the arithmetic mean of expert responses to indicate central tendencies and standard deviations to capture uncertainty. Low variance in opinions was interpreted as a strong consensus. 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). To assess this potential group-level bias, we compared individual versus collective means. We used years of experience reported by experts as a relative proxy for confidence in our analysis outcomes.
2. **Qualitative analysis.** For open-ended questions, we analyzed individual responses thematically to capture explanatory insights and emerging issues not covered by closed-ended questions.
3. **Geospatial and network analysis.** We linked responses containing geospatial information (e.g., crop loss estimates, seed use) to district polygons using the rgeoboundaries package (Runfola et al.,

2022). Using the biscale package, we also generated a bivariate mapping to compare crop loss estimates against the number of responses. Network visualizations of seed and grain exchange represented locations as nodes and expert-reported flows as directed links. Stakeholder networks represented actor categories (policy, research, industry, farmers) as nodes and their reported interactions (communication or wheat exchange) as links.

We performed all analyses and visualizations in R 4.3.3 using the packages ggraph, ggplot2, igraph, sf, terra, and tidyverse. Code, data, and detailed assumptions for reproducibility are publicly available at https://github.com/GarrettLab/Wheat-health-in-Pakistan.

Mapping wheat cropland connectivity. To complement expert knowledge elicitation, we assessed the potential for pathogen or pest spread across Pakistan's wheat landscapes using the geohabnet R package (Keshav et al 2025). Cropland connectivity analysis provides a network perspective into how the spatial configuration of wheat production zones may facilitate or constrain epidemic dynamics (Xing et al 2020).

We used the 2023 AsiaWheat dataset, which maps the fractional area cover of winter wheat at 250-m spatial resolution across Asia. The dataset was projected to the standard coordinate reference system (EPSG:4326) and aggregated to 5 km grid cells for analysis. We selected locations with 5% wheat coverage to represent epidemiologically relevant wheat areas. Using geohabnet, we then calculated connectivity scores to assess the relative likelihood of pest or pathogen movement based on host availability (fractional cropland cover) and dispersal kernels as functions of spatial proximity. These connectivity scores evaluate the importance of a host location when a wheat-specific pathogen or pest reaches that target location. Code, dispersal kernels, network metrics, and the sensitivity analysis used to reproduce the cropland connectivity analysis are publicly available at https://github.com/GarrettLab/Wheat-health-in-Pakistan**.**

Evaluating introduction risks through international trade patterns. Beyond local spread, we also assessed the potential for pathogen introduction through international trade. The alarming emergence of wheat blast in Bangladesh in 2016, associated with South American origin, underscored the risks posed by global seed trade pathways, emphasizing the need for strict phytosanitary safeguards to prevent transcontinental spread of this destructive disease (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) for 2013-2022, using the 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 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. For this analysis, we assume that no pathogen-specific phytosanitary measures are currently applied to international wheat trade.

We combined these geographic risk factors to evaluate the introduction potential of MoT to all wheat-producing countries, and a focused analysis for Pakistan. While MoT served as the case study for understanding its potential spread through international commodity trade, the same framework can be applied to other seedborne or seed-transmitted wheat pathogens or pests. Importantly, if primary inoculum is introduced in Pakistan, the absence of phytosanitary measures could allow long-distance dissemination of MoT through the domestic trade of wheat seed, representing a major vulnerability in national biosecurity.

RESULTS

Spatial Patterns of Crop Losses Caused by Wheat Diseases and Pests

First, we report expert-assessed district-level estimates of crop yield losses caused by eight major diseases or pests for 2018-2022. Most experts estimated stripe rust as the disease causing the highest mean losses in wheat yield nationally (Figure 1), with hotspots in central and eastern Punjab and parts of upper Sindh. Leaf rust was widespread, with high mean losses in southern and southeastern Sindh and moderate impacts in central and eastern Punjab (Figure 1). Stem rust losses were medium (~1.5–2%) across Pakistan, with localized damage in central and southern Punjab, Khyber Pakhtunkhwa (KPK), and southern Sindh.

Fusarium head blight, although less frequently reported, was important in some districts of Punjab and KPK. Karnal bunt was reported to have medium losses (1.5-2.0%) in southern Sindh and parts of northern KPK and low yield losses in parts of Punjab. Loose smut was reported least frequently, with localized impacts in northern Punjab and southern Sindh. Aphids were widely distributed, with moderate losses in central Punjab and Sindh, but low losses (<1.0%) in Balochistan and KPK.

Armyworm outbreaks were reported more scattered, with moderate losses in some districts of central and southern Punjab, as well as northeastern Sindh. Overall, Punjab and Sindh emerged as the wheat-production regions most impacted by multiple threats.

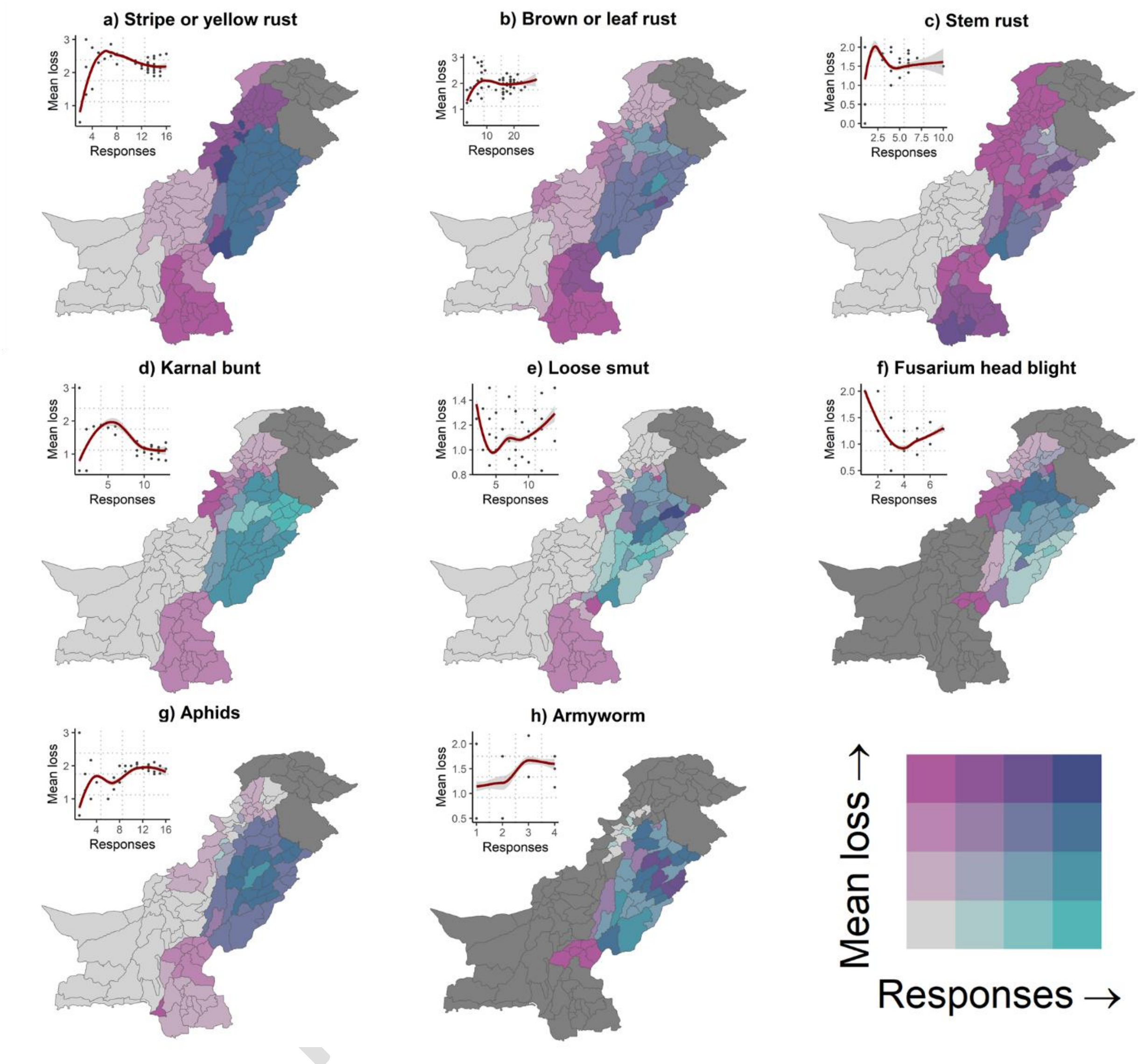

Figure 1. Expert-estimated crop losses (%) caused by eight major wheat diseases and pests in 2018-2022. Colors indicate mean estimated losses (vertical axis of legend), while shading intensity also reflects the number of expert responses (horizontal axis of legend). Insets show mean loss values relative to the number of responses. For example, the darkest blue in the legend indicates a region with high mean crop loss (~3%) and many expert responses (16) for stripe rust. Districts in dark grey are regions where no experts responded in the expert knowledge elicitation.

Importance of Driving Factors in Yield Losses

To complement national loss estimates, we synthesized expert perceptions of the relative importance of seven main agronomic and biological drivers influencing wheat disease and pest outbreaks (Fig. 2). We analyzed expert responses separately from individual experts (n = 28) and five small groups, covering the same high-priority threats described above. For quantitative comparison, experts ranked each driver on a predefined scale from 0 (no importance) to 10 (high importance).

Across both individual and group assessments, experts ranked climate change as the most influential driver, with consistently high scores for rust diseases, aphids, karnal bunt, and armyworm (scores > 8, Fig. 2). Low standard deviations across responses indicated a strong consensus for these threats. Pathogen sub-populations also received high influence scores (mean > 8), especially for the major fungal diseases (rust diseases and karnal bunt). The perceived influence of subpopulations was low for armyworm and wheat aphids.

Other drivers were perceived as moderately important and context specific. Sowing time was strongly associated with yield losses to aphids and leaf rust but was less relevant for karnal bunt and Fusarium head blight. Resistance gene deployment had a moderate influence on rust diseases, while pesticide use was moderately important for loose smut and aphids. Fertilization was generally rated as a low importance driver for most diseases, except for wheat aphids, where nitrogen use was associated with pest outbreaks. Alternative hosts were given limited importance overall.

The individual expert responses largely supported group findings but revealed greater variability, as reflected by higher standard deviations (Fig. 3c-d). Our analysis indicates that while consensus exists on the potential major influence of climate change and pathogen sub-populations, expert views diverge more on agronomic factors such as sowing time, fertilization, and pesticide use.

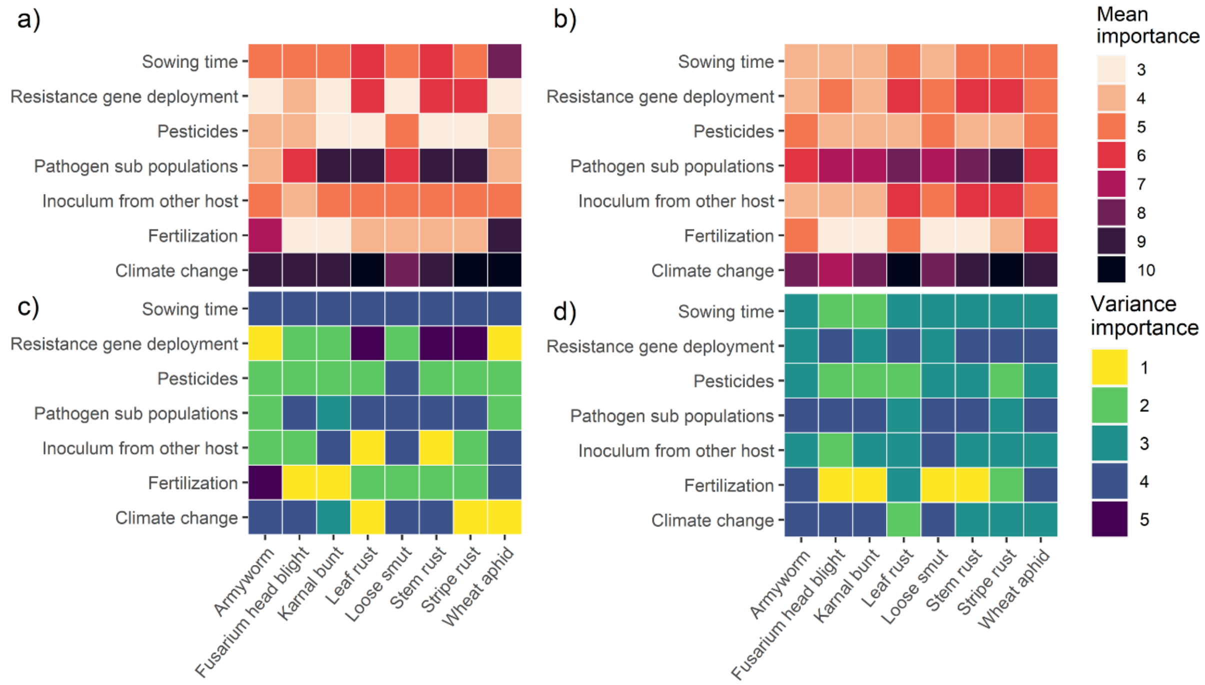

Figure 2. Expert-estimated importance of epidemiological factors driving yield losses of major diseases and pests in Pakistan. a) Mean across group assessments, b) mean across individual assessments, c) variance across group assessments, and d) variance across individual assessments.

Geographic Patterns of Certified Wheat Seed Use

Expert assessments revealed important spatial differences in the use of certified wheat seed across Pakistan (Fig. 3). These patterns were broadly consistent across group-based and individual responses though individual assessments captured greater variability. High adoption (> 30%) was concentrated in Punjab districts such as Lahore, Gujranwala, Hafizabad, Sahiwal, Kasur, and Sheikhupura. These areas showed low variability across responses, indicating strong agreement that they function as major regions of certified seed use. Moderate adoption (15-25%) was reported in central Punjab (e.g., Dera Ghazi Khan, Khanewal, and Jhang), though these estimates were more variable among experts. In contrast, Balochistan and some peripheral districts had low adoption rates (<15%) and greater uncertainty given the high standard deviations in expert assessments.

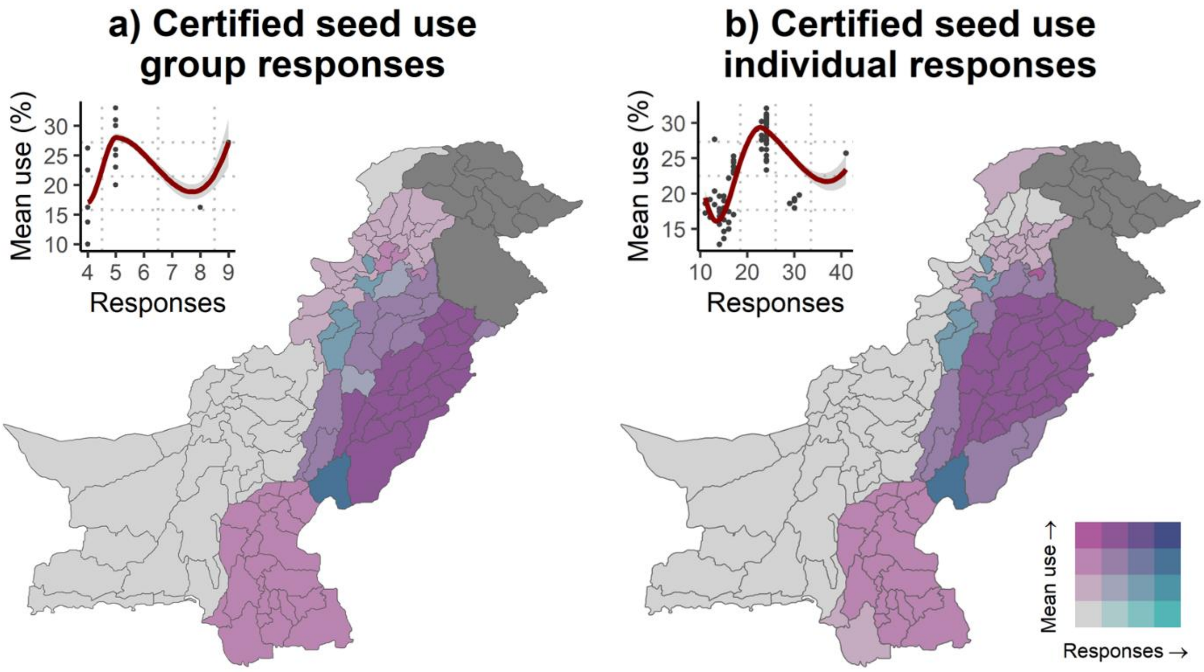

Figure 3. Expert-estimated mean use (%) of certified wheat seed in Pakistan for 2018-2022, based on (a) group responses and (b) individual responses. Insets show mean values relative to the number of responses. Dark grey indicates no data collected for these regions.

Comparison between types of expert assessment showed that group responses tended to have lower variation, while individual estimates highlighted greater district-level heterogeneity (e.g., in Lodhran, Rawalpindi, and Bahawalnagar). Both group and individual assessments, however, provide strong support that Punjab serves as a hub of certified seed use, while areas in Balochistan and peripheral regions remain underserved.

Seed Exchange Networks

Experts reported a highly interconnected network, in which wheat seed exchange occurred among provincial, national, and international agroecosystems (Figure 4). Group assessments reported a much denser network of 61 trade links (25% formal, 34% informal, and 41% mixed connections), while individual assessments reported a much denser network of 133 trade links (29% formal, 40% informal, and 30% mixed connections). We used the number of trade links of a node (i.e., node degree) as a measure of the relative importance of a location in the seed exchange network. In both group and individual 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 major roles as net seed sources, either formally or informally, having twice as many export links as import links. The Federal territory acted as a key bridge of seed exchange, linking peripheral regions such as Gilgit-Baltistan (GB) and Azad Jammu & Kashmir (AJK). International connections were less likely than domestic trade, but not negligible. India had twice as many export links with Pakistan as import links. Pakistan had twice to four times more export links with Afghanistan and Iran than import links, mainly via informal routes.

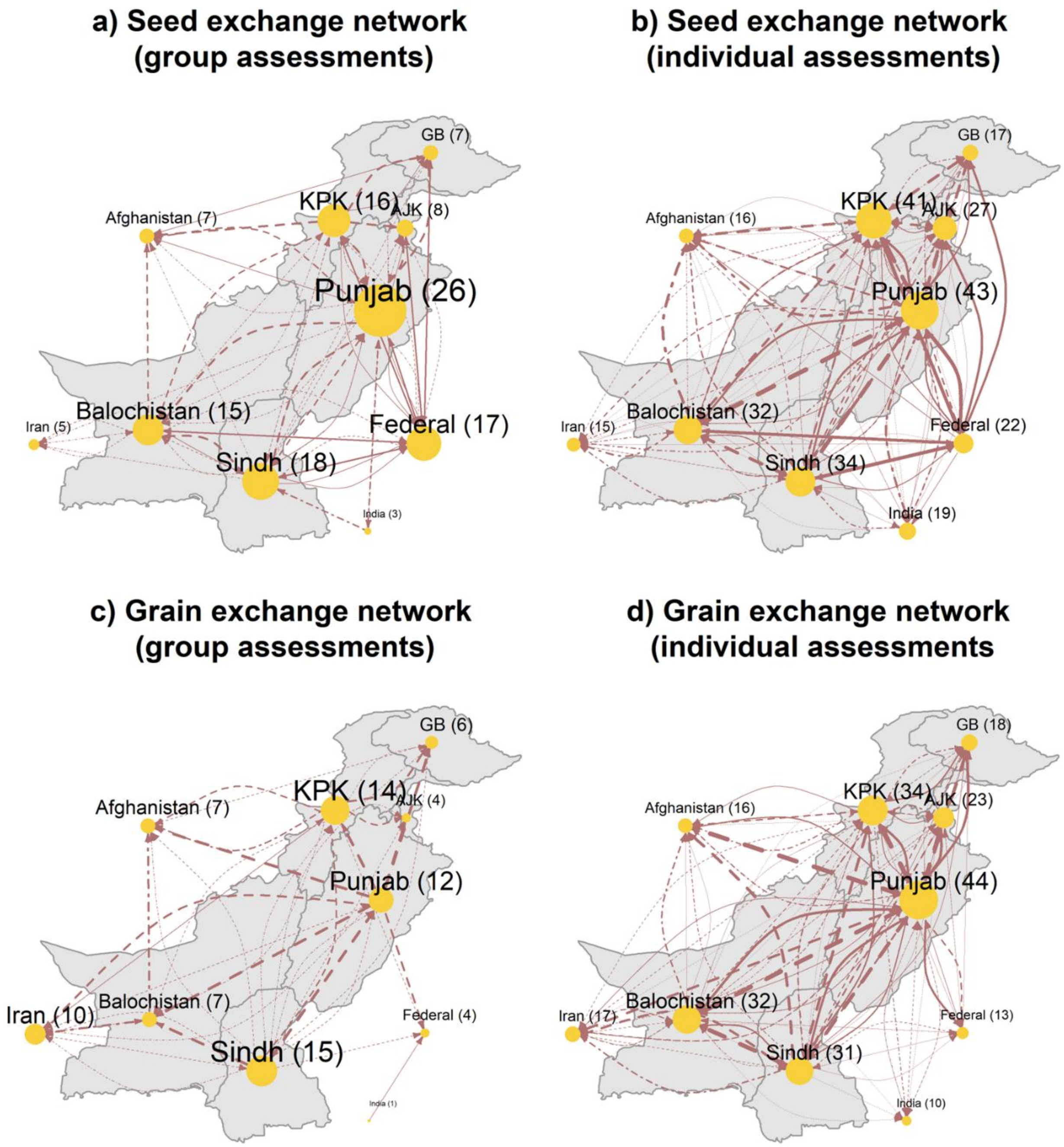

Figure 4. Expert-reported networks of wheat seed (a-b) and grain (c-d) exchange in Pakistan for 2018-2022, based on group and individual responses. Node size is proportional to the number of connections of a region (degree), as indicated within parenthesis. Line types indicate formal-only (solid), informal-

only (dashed) and mixed (dotdashed) trade. Abbreviations: AJK = Azad Jammu & Kashmir, KPK = Khyber Pakhtunkhwa; GB = Gilgit-Baltistan.

Grain Exchange Networks

The grain exchange network was sparser than the seed network (Fig. 4). The grain exchange network consisted of 40 trade links (3% formal, 30% informal, and 67% mixed connections) based on group responses, whereas individual responses identified 119 trade links (32% formal, 27% informal, and 41% mixed connections). Group responses indicated fewer formal trade links (36%) than those captured by individual expert opinions (52%). In both group and individual responses, Punjab was again a major hub of wheat grain trade, acting as a recipient and a source. Punjab had trade connections with nearly all other regions (except India for the group assessment).

Likewise, experts reported that Sindh and KPK act as net grain sources, having up to six times as many export links as import links. Other regions, including Balochistan, AJK, GB, and the Federal territory, were net recipients, highlighting their dependence on imports from net sources. At the international level, Afghanistan, India, and Iran acted primarily as recipients of Pakistani wheat grain, particularly through informal trade channels.

Together, these networks revealed the coexistence of informal and formal channels in both seed and grain movement, whether domestically or internationally. While certified seed use remains concentrated in Punjab (Fig. 3), the informal exchange of wheat commodities is likely common both nationally and internationally (Fig. 4). These mixed wheat systems create opportunities for the dissemination of improved varieties but also represent potential pathways for the spread of seedborne pathogens.

Stakeholder Interaction Networks

Our analysis of stakeholder interactions in Pakistan's wheat sector identified the key roles of stakeholders in networks for both information exchange and movement of planting material (Fig. 5). Together, these interaction networks revealed a wheat system that is highly connected but reliant on a few central actors, particularly farmer associations and seed dealers.

1. Plant material exchange. The plant material exchange network illustrated the directional flow of seed transactions among key stakeholders involved in Pakistan's wheat system. Seed users were the most connected actors, receiving material from nearly all other stakeholders. Farmer associations and seed dealers had high centrality, acting as intermediaries between formal institutions (e.g., research bodies, NGOs) and end users. Policymakers had few connections.

National and international research institutions, along with specialized seed producers, shared plant materials with public and private food sectors, policymakers, and seed dealers, playing upstream roles in seed development and dissemination. Both public and private food sectors are well-connected and act as bridges between policymakers and operational-level stakeholders, such as dealers and users. While most experts agreed that there is mutual exchange of planting materials between national and international research institutions, only few experts indicated that policymakers had connections with other stakeholders.

2. Information exchange. The information exchange network had more connections between stakeholders than the planting material exchange network (Figure 5). Farmer associations, seed users, seed dealers, policymakers, and research institutions (both national and international) played key roles as central nodes. Farmer associations and seed dealers were particularly important conduits, linking both upstream (research, policy) and downstream (users, producers) entities.

Bidirectional flows were reported between farmer associations, seed dealers, and both public and private food sectors. National research institutions and NGOs also played critical bridging roles, linking international research and specialized seed producers, and influencing evidence-informed decision-making across the sector.

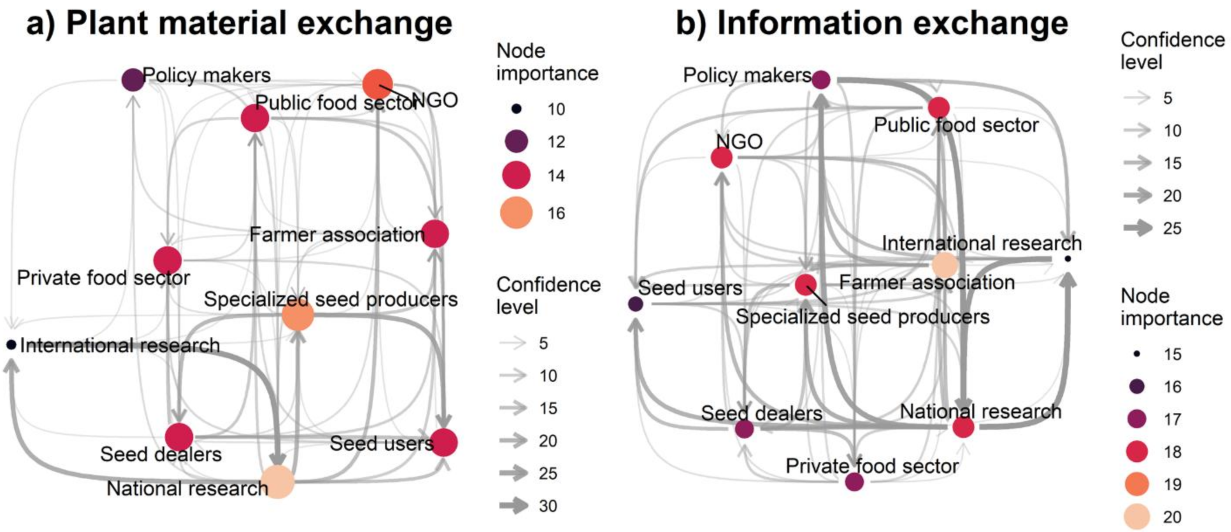

Figure 5. Networks of (a) plant material exchange and (b) information exchange among stakeholders in Pakistan's wheat system. Node importance indicates the total number of connections from or to a stakeholder. Arrow thickness represents the number of experts reporting a connection (confidence level).

Wheat Cropland Connectivity in Pakistan

Connectivity scores indicate the relative potential for disease or pest spread, based on wheat host availability and proximity of host areas (Fig. 6a). High cropland connectivity (0.8-1.0) characterized a north-south corridor that extends from wheat-intensive districts in northern Punjab through central Punjab into parts of southern Punjab and northern Sindh. This densely connected corridor comprises a belt of uniformly contiguous wheat-growing regions, including Bahawalnagar, Gujranwala, Hafizabad, Lodhran, and Nankana Sahib.

Some regions of upper Sindh (such as Sukkur and Ghotki), lower KPK (including Swabi and Mardan), and Punjab (like Attock) have medium cropland connectivity (0.5-0.7). Wheat cultivation is important in these regions, but the wheat landscape is less continuously distributed compared to central Punjab. Western Balochistan, the mountainous areas of Gilgit-Baltistan, and upper KPK had low connectivity scores (≤0.4). These regions reflect a spatially fragmented landscape and less dense croplands with potentially reduced chances for pathogen or pest spread.

Together, our cropland connectivity analysis revealed a highly uneven spatial distribution of wheat connectivity, closely aligned with the country's major production landscapes. Additionally, high levels of cropland connectivity generally overlap with high disease pressure in Punjab and Sindh (Fig. 6a-b).

Introduction potential of *Magnaporthe oryzae* pathotype *Triticum*

To complement cropland connectivity analysis, we estimated the relative introduction potential of wheat blast (MoT) into Pakistan and globally (Fig. 6c). This analysis indicates that Pakistan has been moderately vulnerable to MoT introduction even in the absence of pathogen-specific phytosanitary measures in place. Despite having large wheat-growing areas, Pakistan formally imported wheat seeds from Mexico, Turkey, and Lebanon during the period from 2013 to 2022. MoT remains unreported in these countries that exported seeds to Pakistan.

In comparison, re-introduction potential remains high for South Asian neighbors such as Bangladesh and India. MoT has already been reported in these countries, which have large wheat-growing areas and strong connections in the wheat seed network (Fig. S1). Our analysis also highlighted South American countries, where MoT is endemic, and Zambia as a potential source of inoculum. If these patterns in international trade of wheat seed continue and no MoT-specific phytosanitary efforts are in place, there is the possibility for MoT to be introduced in many wheat-producing countries, including Pakistan.

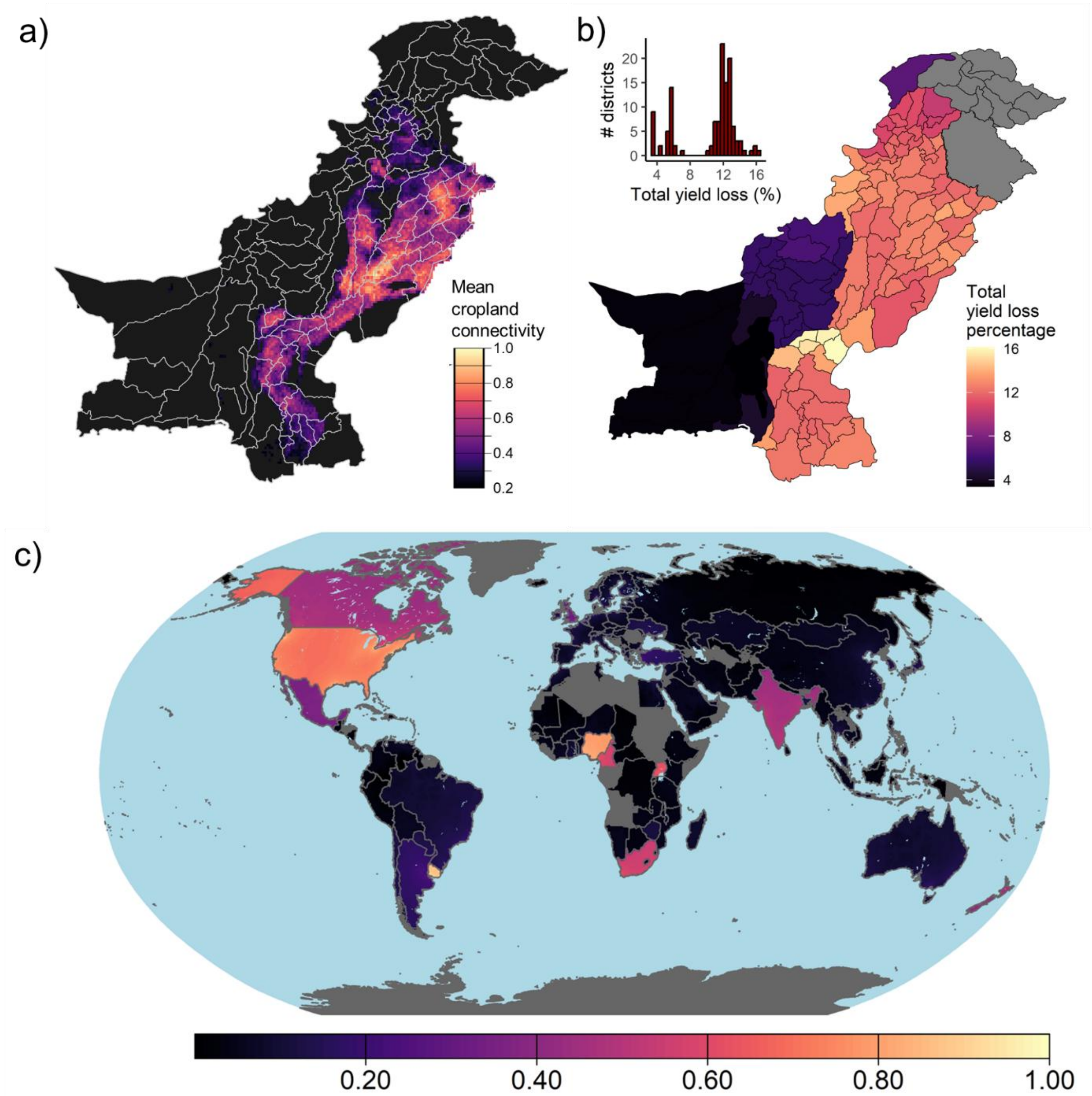

Figure 6. a) Mean cropland connectivity scores for Pakistan, indicating the relative potential for the spread of wheat-specific pathogens and pests across production zones. b) District-level cumulative yield losses (%) to eight major wheat diseases and pests for 2018-2022, based on arithmetic averages of individual expert assessments. c) Global relative risk of wheat-producign countries to the potential introduction of Magnaporthe oryzae pathotype Triticum (MoT). *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.*

DISCUSSION

This study provides the first integrated expert-based assessment of wheat health risks in Pakistan. In this expert-based assessment, 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). Loose smut, stem rust, Fusarium head blight, and armyworm, however, showed specific geographic patterns. Experts also evaluated risk factors influencing pathogen and 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 Pakistan's 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 the spread of established and emerging threats. This collective expert knowledge provides a rapid approach to understanding the potential spread of pests and pathogens on a large scale, as well as 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 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 with hotspots in Punjab and Sindh (Figs. 1, 6). 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 expected to facilitate reproduction of pathogens and pests, lengthen seasonal windows for disease and pest development, extend pest distributions, and modify the virulence of pathogen strains (Jonathan & Mahendranathan, 2024; Lahlali et al., 2024).

The genetic variability of pathogen sub-populations was the second most important driver of wheat yield losses, reflecting long-standing concerns about potential erosion of disease resistance in Pakistan. 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), challenging durable epidemic management in the region (Khan et al 2020). Enhanced geographic monitoring of pathogen populations will aid national programs in the strategic deployment of resistant cultivars and the anticipation of seasonal shifts of optimal infection conditions.

Other agronomic factors were considered moderately important and context dependent. Experts 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 (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 countries like Iran and Argentina (Naseri and Sasani 2020, Moschini and Pérez, Gebrel et al 2018), reinforcing expert opinions in Pakistan. Deployment of resistance genes has allowed 5-10% reduction in disease severity, particularly against leaf and stripe rust, in South Asia, through collaborations with CIMMYT. However, effectiveness 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 alternative hosts were generally considered to have a low influence, possibly indicating reduced chemical efficacy (Khan et al., 2021) and limited pathogen sharing across non-wheat hosts.

Estimated losses from multiple threats overlapped in Punjab and Sindh, underscoring the substantial vulnerability of these intensively cultivated areas with narrow genetic bases and high agricultural inputs. By contrast, consistently low losses reported for Balochistan and parts of the tribal belt are likely attributed to climatic constraints to pathogen development, lower wheat productivity, and limited surveillance (Ghulam Murtaza Safi et al., 2014)(Akhter & Mirza, 2006).

Perspectives on seed health management. For the first time, this study characterizes two core components of the wheat seed system in Pakistan as proxies for seed health: certified seed adoption and seed/grain exchange networks.

Certified seed adoption reduces the likelihood of pathogen or pest introduction and establishment at the farm, district, and national levels. Districts with a high mean in certified seed use, like Lahore and Gujranwala, showed strong agreement across expert assessments. High certified seed adoption reflects a greater influence of formal seed systems in these regions, possibly underpinned by strong institutional support and robust varietal deployment (McEwan et al., 2021). Districts like Lodhran or Khanewal with moderate certified seed adoption exhibited greater variability, likely indicating uneven adoption and 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, and farmer outreach (Rai et al., 2020). Expanding certified seed adoption in these underserved areas presents a key opportunity to strengthen national disease management.

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

Our spatial network analysis indicates that Punjab acts as a major hub for seed and grain exchange, consistent with its large wheat-producing area. Three main formal deployment mechanisms operate (Siddiqi et al., 2024a;Ali, 2013): (i) private commercialization through the Punjab Seed Corporation, (ii) CIMMYT-led community-based seed multiplication, and (iii) farmer-based certification models linking growers with companies or government agencies.

Informal wheat exchange remains a backbone of seed distribution, fulfilling gaps in varietal access in many rural areas (Tu et al., 2024) but raising phytosanitary concerns. Informal seed exchange may unintentionally facilitate the geographic translocation of seed-associated pathogens and pests (Hernandez Nopsa et. al., 2015). Experts estimated that 70-75% of seed and 68-97% of grain exchanges occur informally (Fig. 4). Historical examples illustrate this seed-mediated epidemic potential. The spread of *T. indica* in South Asia demonstrated how farmer-to-farmer exchange can drive regional epidemics (Singh et al 1989) and restrict international trade of wheat seed (Bishnoi et al 2020). Our analysis further identified KPK and Sindh as net seed sources and the Federal Territory as a potential strategic bridge in the seed system. These roles (hubs, sources, or bridges) are consistent across both the formal and informal systems.

The grain trade network showed a similar pattern, with informal exchanges from Punjab and Sindh into other provinces. While grain for consumption poses a lower on-farm risk of seedborne disease transmission, it can still facilitate the movement of storage pests and lead to post-harvest losses. While we focused on the presence or absence of wheat exchange, future studies could characterize the frequency and volume of seed movement. Strengthening market regulation and post-harvest quality assurance remains a key challenge.

Together, these findings emphasize the need for a hybrid approach to seed health management within the national wheat system (e.g., Andersen Onofre et al 2021). A hybrid approach would be key to effectively addressing unintentional phytosanitary issues in seed systems while maintaining farmer access to improved varieties. 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.

Perspectives on stakeholder networks. Stakeholder networks are crucial for the effective dissemination of management information and planting material (Garrett 2021). Characterizing past interactions between stakeholders allowed us to identify key roles of stakeholders in information sharing and plant material exchange.

In the information exchange network, almost all stakeholders were reported to interact reciprocally, particularly between national and international research stakeholders. Most experts 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). Farmer associations, NGOs, and seed dealers acted as important intermediaries, likely channeling information from research and policy actors to seed users and producers. Policy makers are likely to serve as net sources of information to other stakeholders, although few experts reported these connections. In the plant material exchange network, seed users and the private food sector are likely to be net recipients from any stakeholders. Farmer associations, seed dealers, and specialized seed producers serve as trade hubs, exchanging plant material with other stakeholders.

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. While net recipients would be required to reach out to other stakeholders to acquire new management information or breeding technologies, hubs could facilitate the sharing of these resources throughout the network. Likewise, NGOs emerged as key partners for coordinating the dissemination of plant material and management information, especially in the context of disasters and emerging disease outbreaks (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 links with national research organizations. Strengthening these connections could ensure that biosecurity and varietal deployment policies are better informed by farmer experiences. Likewise, expanding direct links between farmer associations and international research could accelerate varietal development, redistribution, and phytosanitary regulation.

Taken together, farmer associations and seed dealers are key points for surveillance and mitigation, while greater integration of policymakers is important for improved communication and preparedness. Further research efforts may be needed to characterize 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, particularly along the Indus River basin (Gumma et al., 2019; Siddiqi et al., 2024b).

Central Punjab and northern Sindh emerged as highly connected areas along the major wheat-production belts, coinciding with expert-estimated yield losses (Fig 1). Districts such as Hafizabad, Nankana Sahib, Multan, Lodhran, and western Bahawalpur have high cropland connectivity and high cumulative losses across diseases and pests (Fig. 6b). 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).

Regions having moderate cropland connectivity, such as northern Sindh and parts of Khyber Pakhtunkhwa, are associated with moderate yield losses (Fig. 6b). These relatively fragmented regions may allow more effective containment if outbreaks are detected early (Xing et al., 2020c; Zadoks et al., 1995) (Papaïx, 2011). Low-connectivity areas such as western Balochistan and the northern mountainous regions of Gilgit-Baltistan exhibited consistently low yield losses, with natural barriers and isolated wheat fields likely limiting pathogen movement (Batool et al., n.d.; Tuladhar et al., 2023; Xing et al., 2020c).

Interestingly, Ghotki, Jacobabad, and Kashmore have relatively low cropland connectivity, but they experienced the highest cumulative yield losses. Possibly, these regions serve as an effective structural bridge for pathogen or pest movement between wheat production areas in Punjab, Sindh, and Balochistan. This pattern highlights the importance of integrating network analysis with expert assessments to identify "hidden" epidemiological corridors.

Provinces having high cropland connectivity (central Punjab and northern Sindh) are also major hubs for seed and grain movement, both formal and informal. Transboundary exchange of planting material across neighboring well-connected regions is also important for developing prevention strategies against invasive pathogens and pests. Overall, the spatial overlap between high cropland connectivity and major production hubs underscores the need for coordinated surveillance, resistant cultivar deployment, and rapid response capacity in these corridors.

Perspective on wheat blast introduction. Our introduction risk assessment for wheat blast highlights Pakistan's current moderate vulnerability to incursion via international seed trade (Fig. 6c). Between 2013 and 2022, Pakistan formally imported wheat seed only from Mexico, Turkey, and Lebanon, none of which have reported MoT presence. There is no formal international trade of wheat seed with countries where MoT is reported to be present (Argentina, Bangladesh, Bolivia, Brazil, and Zambia). Similarly, a global study 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, future risks cannot be discounted. More humid and warmer conditions are projected to make some wheat production areas in Pakistan likely vulnerable to wheat blast infection by 2040-2070 (Pequeno et al 2024). Informal transboundary movement of wheat seed, particularly from India, is a possibility (Fig. 4). Should wheat blast continue to spread eastward across India, these informal channels increase the likelihood of eventual occurrence in Pakistan. The probability of host jump from rice to wheat cannot be excluded, as rice blast is present in Pakistan. Both hosts (rice and wheat) and pathogens (*Pyricularia oryzae* and *Pyricularia oryzae* triticum) are taxonomically closely associated (Ioos and Tharreau, 2025).

Robust biosecurity efforts are active across the border between India and Bangladesh, following a recent incursion of wheat blast in this region (Das 2017). A comparable strategy in South Asia could be coordinated across Pakistan, India, and Bangladesh and build collective preparedness against future wheat blast outbreaks. Farmers and extension agents in Pakistan should remain proactively vigilant for the potential appearance of disease symptoms suggestive of wheat blast.

Beyond MoT, future studies could use the introduction framework for other seedborne pathogens. Wheat pests may enter a country, either naturally crossing contiguous wheat landscapes at geopolitical borders or introduced unintentionally via the international trade of high-risk commodities. Our analysis illustrated how international trade and informal exchange interact with national seed systems, creating multiple layers of vulnerability to pathogen incursion.

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.

Expert elicitation depends on the representativeness of participants and captures perceptions and experiences rather than objective measures, which can potentially introduce biases. To strengthen findings, future studies could combine expert knowledge with empirical data sources such as national farmer surveys, pathogen population genomics, and remote sensing. Future elicitation could also include social dimensions such as smallholder participation in surveillance and gender-inclusive extension services.

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.

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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

Iqbal, M. J., Ahmad, I., & Khanzada, K. A. (2010). Local stem rust virulence in Pakistan and future breeding strategy. *Pakistan Journal of Botany*, 42(3), 1999–2009. https://www.pakbs.org/pjbot/PDFs/42(3)/PJB42(3)1999.pdf

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.

Rehman, M. U., Gale, S., Brown-Guedira, G., Jin, Y., Marshall, D., Whitcher, L., Williamson, S., Rouse, M., Ahmad, J., Ahmad, G., Shah, I. A., Sial, M. A., Rauf, Y., Rattu, A. U. R., Mirza, J. I., Ward, R., Nadeem, M., Ullah, G., & Imtiaz, M. (2020). Identification of seedling resistance to stem rust in advanced wheat lines and varieties from Pakistan. *Crop Science*, 60(5), 2390–2405. https://doi.org/10.1002/csc2.20217

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