

Article

Occurrence, Provincial Spatial Patterns, and Statistical Co-Occurrence of Diseases and Insect Pests in Foxtail Millet Across Northern China

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Abstract

Foxtail millet (*Setaria italica* L.) is a key dryland cereal in northern China yet multi-regional information on its disease–pest complexes remains limited. Using a 2025 field-monitoring dataset from 84 sites in 11 provincial-level regions, this study assessed the occurrence spectrum, regional variation, relative pressure, provincial spatial patterns, complex types, and statistical co-occurrence associations of major diseases and insect pests observed during a single grain-filling-stage survey. Field records were standardized numerically, and richness metrics, relative pressure indices, complex-type classification, provincial mapping, and binary correlation analysis were applied. Foxtail millet blast, millet downy mildew, and foxtail millet sheath blight were the dominant field-diagnosed disease categories, with occurrence rates of 97.18%, 89.74%, and 73.02%, respectively. Stink bug-related records represented by the hyaline grass bug, double-spotted long-tarsed leaf beetle records, armyworm records, foxtail millet leaf beetle records, and Asian corn borer records were the most common insect pest variables. Northeast China showed higher disease richness and total disease–pest richness, while Northeast China and the North China–Huang-Huai region had higher total disease–pest pressure. Pest-dominated sites accounted for 47.62% of all sites. Co-occurrence analysis identified strong positive statistical associations, particularly between millet downy mildew and stink bug-related records. These results provide a grain-filling-stage monitoring baseline for foxtail millet disease–pest complexes and support integrated monitoring, regional surveillance, and exploratory classification-based interpretation. The findings should be interpreted as cross-sectional field-monitoring results rather than evidence of seasonal dynamics, causal disease–pest interactions, or validated control thresholds.

Keywords: foxtail millet; disease–pest complex; integrated pest management; field monitoring; co-occurrence analysis



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1. Introduction

Foxtail millet (*Setaria italica* (L.) P. Beauv.) is one of the oldest domesticated cereal crops and has long supported dryland agriculture and food systems across Eurasia. Archaeological and crop-evolution studies have shown that millets of the genera *Panicum* and *Setaria* have a long cultivation history and wide geographical distribution, with foxtail millet closely linked to early agricultural development in Asia [1,2]. Recent studies and reviews have further summarized its origin, diversity, genetic improvement, genomic resources, and role in dryland agriculture [3–6]. Beyond its historical importance, foxtail millet is valued as a drought-tolerant and stress-adaptive cereal crop. Genomic, pan-genomic, population-level, and germplasm studies have revealed substantial genetic diversity, domestication-related variation, local adaptation, and agronomically important traits in foxtail millet [7–12]. This variation helps explain its stable cultivation across contrasting ecological regions. These characteristics make foxtail millet particularly important in arid and semi-arid agricultural systems, where crop stability and resilience are major production concerns.

Despite its adaptability, foxtail millet production is constrained by several diseases and insect pests. Previous studies and reviews have documented that millet crops are susceptible to multiple biotic stresses, and disease and pest management remain an important component of sustainable millet production [13–16]. For foxtail millet, major diseases include blast, rust, downy mildew, sheath blight, smut, and ear rot. Research has addressed several of these diseases from different perspectives, including the status and management of foxtail millet blast [17], metabolite responses associated with blast pathogen infection [18], the identification of blast-resistance loci [19], the interaction between foxtail millet and *Uromyces setariae-italicae* [20], the genome and effector repertoire of *Sclerospora graminicola* [21], the suppression of host defense responses by *S. graminicola* [22], the genome resource of *Ustilago crameri* [23], and the pathogenicity of *Curvularia geniculata* causing foxtail millet ear rot in China [24]. Recent studies on millet downy mildew have also shown that cropping systems, rhizosphere microbial communities, and host resistance are closely related to disease suppression or resistance [25,26]. Biological control studies on banded sheath blight in little millet and foxtail millet further indicate that low-residue and biologically based management options are being actively explored [27]. These studies provide disease-specific evidence, but they do not fully characterize field-level assemblages of multiple diseases across regions.

Insect pests also constrain millet and foxtail millet production. General studies on millet insect pests have emphasized the economic importance of stem borers, shoot flies, leaf-feeding insects, and sucking pests. They have also highlighted the need for integrated pest management [14]. Greenhouse-based observations have confirmed that foxtail millet can host diverse pests and diseases, underscoring the need for reliable field identification before management decisions are made [13]. In China, local studies have reported the occurrence and damage of foxtail millet diseases and insect pests in production areas such as Lüliang, Xinzhou, Taigu, Datong, and Hengshui [28–32]. These studies show that foxtail millet fields are commonly affected by multiple diseases and pests, including millet downy mildew, foxtail millet blast, foxtail millet smut, millet stem borer, foxtail millet leaf beetle, armyworm, Asian corn borer, and double-spotted long-tarsed leaf beetle. However, most Chinese studies have focused on local occurrence surveys, pest population dynamics, or control practices. Few have evaluated disease–pest complexes across multiple ecological regions using a unified analytical framework.

For field-based crop protection, diseases and pests should be evaluated not only by the presence of individual species but also by their combined occurrence, regional differentiation, and relative pressure. Integrated pest management emphasizes coordi-

nated monitoring and management of pest populations within agroecosystems [33–36]. Plant disease epidemiology highlights disease occurrence, spread, and management at population and field scales [37–40]. In practice, diseases and insect pests often occur simultaneously. Their observed associations may reflect shared environmental conditions, crop growth stages, cultivar susceptibility, cropping systems, or management practices. Therefore, analyzing disease–pest complexes from a multi-regional perspective can help identify dominant biotic stressors, clarify regional differences, and support region-specific monitoring and control strategies.

Co-occurrence analysis provides a useful exploratory approach for identifying disease and pest combinations that tend to appear together. Ecological studies have used co-occurrence analysis to examine non-random associations among species. These studies also caution that co-occurrence patterns do not necessarily indicate direct biological interaction or causality [41–43]. For binary occurrence data, correlation-based approaches can describe pairwise associations among diseases and pests, provided that multiple testing and interpretation limits are properly considered [44,45]. In addition, when multi-factor risk models are developed in future work, potential collinearity among environmental, agronomic, and management variables should be carefully evaluated [46]. In the present study, co-occurrence analysis was used as an exploratory tool to identify disease–pest combinations that may require joint monitoring, not as evidence of causal relationships.

Although previous studies have improved understanding of foxtail millet evolution, disease resistance, pest occurrence, and disease or pest management, multi-regional quantitative assessments of disease–pest complexes in foxtail millet remain limited. In particular, there is still a need to integrate occurrence spectrum analysis, regional comparison, relative disease–pest pressure, site-level complex classification, spatial visualization, and co-occurrence analysis within a single field-monitoring framework. Based on the geographically heterogeneous agroecological conditions across northern China and previous evidence that foxtail millet fields are affected by multiple diseases and insect pests, we formulated three hypotheses: (1) major diseases and insect pests of foxtail millet show distinct regional and provincial occurrence patterns during the grain-filling stage; (2) disease and pest pressure differ among survey sites, resulting in disease-dominated, pest-dominated, and relatively balanced disease–pest complex types; and (3) some diseases and insect pests show significant statistical co-occurrence across survey sites, although such associations may reflect shared environmental, agronomic, or management-related conditions rather than direct biological interactions. Therefore, this study was designed to: (1) characterize the occurrence spectrum of major diseases and insect pests in foxtail millet based on multi-regional field monitoring data from 2025; (2) compare disease–pest composition, richness, and relative pressure among the North China–Huang-Huai region, Northeast China, and the Northwest dryland region; (3) classify survey sites into different disease–pest complex types based on relative pressure indices; and (4) identify significant co-occurrence patterns among major diseases and insect pests. The results establish a multi-regional reference for prioritizing surveillance targets, classifying field risk types, and supporting region-specific surveillance and preliminary monitoring-based interpretation of foxtail millet diseases and insect pests.

2. Materials and Methods

2.1. Data Source and Survey Sites

This study was based on a cross-sectional field-monitoring dataset of major diseases and insect pests in foxtail millet collected once in late August 2025, when the crop was at the grain-filling stage. This survey timing was selected because many major diseases and insect pests included in the monitoring checklist are commonly observed or more readily ob-

served during the middle to late growth stages of foxtail millet, when symptoms, damaged organs, and pest occurrence are usually more apparent in the field. In addition, disease and pest occurrence during the middle to late growth stages can have direct relevance to yield formation and harvest-stage field management. Nevertheless, the dataset represents disease and pest occurrence observable during this specific survey period and crop developmental stage, rather than seasonal or annual disease–pest dynamics. The results should not be interpreted as a full-season inventory of all harmful organisms affecting foxtail millet throughout its development. The original monitoring records included basic site information, such as province, city, county or district, township or village, and monitoring station. They also included field records of disease and pest occurrence. Disease-related variables included disease incidence and disease severity for selected diseases. Pest-related variables included insect infestation rate and insect abundance per plant.

A total of 84 valid survey sites were included in the analysis. These sites covered 11 provincial-level regions in northern China: Henan, Hebei, Shanxi, Shandong, Liaoning, Inner Mongolia, Heilongjiang, Jilin, Gansu, Ningxia, and Shaanxi. To compare regional differences in disease and pest occurrence, the survey sites were grouped into three broad regions according to geographic location and foxtail millet production characteristics. The North China–Huang-Huai region included Henan, Hebei, Shanxi, and Shandong. Northeast China included Liaoning, Jilin, and Heilongjiang. The Northwest dryland region included Inner Mongolia, Gansu, Ningxia, and Shaanxi.

2.2. Field Survey Procedure and Assessment Criteria

Field surveys were conducted once in late August 2025, when foxtail millet was at the grain-filling stage. All 84 valid survey sites were investigated under a unified field-monitoring framework. The same sampling design, investigated area, number of examined plants, disease and pest categories, occurrence assessment criteria, and field-recording forms were used across all sites. The surveys were not conducted by a single field team across all provinces; instead, experienced plant protection experts and trained local monitoring personnel followed the same technical protocol and recording requirements. Before field investigation, survey personnel were instructed to use consistent criteria for symptom recognition, pest identification, occurrence scoring, and data recording. Although the exact calendar dates and survey personnel differed slightly among provincial monitoring stations because of local crop phenology and logistical arrangements, all surveys were completed in late August 2025 during the grain-filling stage, which ensured comparability in crop developmental stage among provinces. At each survey site, diseases and insect pests were assessed using a five-point sampling method. Each sampling point covered an area of 4 m², and 100 plants were examined at each site. Three repeated assessments were conducted to improve the reliability of field records.

Disease occurrence was evaluated mainly based on the infected-plant rate. Disease classes were assigned according to the following criteria: class 1, infected-plant rate < 1%; class 3, 1–5%; class 5, 5–25%; class 7, 25–50%; and class 9, >50%. These classes were used to standardize field descriptions and to support subsequent conversion of categorical records into numerical values. Disease severity was additionally recorded for foxtail millet blast and foxtail millet rust, but these severity records were treated as supplementary descriptive variables rather than being incorporated into the main disease pressure index. For insect pests recorded by infestation rate, including foxtail millet leaf beetle, Asian corn borer, millet stem borer, millet shoot fly, armyworm, cotton bollworm, carmine spider mite, corn leaf aphid, rice leaf folder, and single-spined mole cricket, the same five-point sampling method was used. At each sampling point, a 4 m² area was investigated, and 100 plants were examined at each survey site. The number of damaged or infested plants was recorded,

and the infestation rate per 100 plants was calculated. For double-spotted long-tarsed leaf beetle records and stink bug-related records, insect abundance was recorded as the number of insects per plant, based on 100 investigated plants at each survey site. Pest identification was based on expert field identification using direct observation of insects, typical damage symptoms, external morphological characteristics, and the revised monitoring checklist. The monitored insect pests were common and routinely surveyed pest categories in foxtail millet production areas. For pests recorded by infestation rate, the number of damaged or infested plants was recorded, and the infestation rate per 100 plants was calculated. For pests recorded by abundance, the number of visible insects per plant was counted based on 100 investigated plants at each survey site.

Some original monitoring records were recorded at the pest-group level, such as aphids, mites, stink bugs, or mole crickets. Because no voucher specimens, detailed taxonomic examination, or molecular identification were used in this survey, these group-level records were retained as group-level occurrence variables in the analysis. Representative species names were used only for consistency with the revised monitoring checklist and figure labeling, and should not be interpreted as specimen-confirmed species-level occurrence records. The classification criteria for pest occurrence were consistent with those used for disease incidence. Light occurrence was defined as an infestation rate of <1%, whereas light damage without the need for control was defined as an infestation rate of 1–5%. In the field monitoring system used in this study, 5% was treated as the plant protection control threshold. Therefore, disease or pest occurrence below 5% was considered not to require field control. The same occurrence classes were used across monitored diseases and insect pests to standardize field recording and enable comparison within the monitoring dataset. These classes should not be interpreted as evidence that all diseases and pests have identical epidemiological behavior, damage potential, or economic importance. Similarly, the 5% value used in the field monitoring system was treated as a general reference point for distinguishing very light occurrence from occurrence levels that may require attention; it was not used as an organism-specific economic injury level or a validated control threshold. Organism-specific thresholds were not available for all monitored diseases and pests in the present dataset.

Disease and pest identification in this study was based on expert field diagnosis or expert field identification using visible symptoms, typical damage patterns, external morphological features, and the revised monitoring checklist. The monitored diseases and insect pests were common and routinely surveyed disease or pest categories in foxtail millet production areas, rather than newly emerging or previously unreported organisms. For these routine monitoring categories, experienced plant protection experts can generally identify occurrences in the field according to typical symptoms, damaged organs, field appearance, and pest morphology, in combination with published descriptions and monitoring experience [17–24,27–32]. Therefore, the records in this study are suitable for field monitoring and regional comparison purposes.

However, no pathogen isolation, microscopic examination, molecular diagnostic confirmation, voucher specimens, or specimen-based taxonomic verification was performed in this survey. Therefore, the disease and pest records should be interpreted as expert field-diagnosed or expert field-identified monitoring records rather than laboratory-confirmed pathogen records or specimen-confirmed species-level occurrence records. For atypical symptoms, uncertain records, or potentially new disease or pest occurrences, laboratory diagnosis, molecular identification, or specimen-based taxonomic confirmation would be necessary.

2.3. Monitored Diseases and Insect Pests

Nine field-diagnosed disease categories of foxtail millet were included in this study: foxtail millet blast, foxtail millet rust, millet downy mildew, foxtail millet nematode disease, bacterial leaf stripe of millet, foxtail millet sheath blight, foxtail millet smut, foxtail millet ear rot, and red leaf disease. These disease categories followed the revised disease checklist used in the monitoring dataset and were consistent with previous reports on foxtail millet and millet disease occurrence, pathogen biology, resistance, and management [17–24,27]. Disease incidence was recorded for all disease categories. In addition, disease severity was recorded for foxtail millet blast and foxtail millet rust. The pathogen names listed in Table A1 represent checklist-associated or commonly reported causal agents and should not be interpreted as laboratory-confirmed pathogen identification in this survey.

Twelve insect pest variables or pest groups were included: foxtail millet leaf beetle, Asian corn borer, millet stem borer, millet shoot fly, armyworm, double-spotted long-tarsed leaf beetle, stink bug-related records represented in the monitoring checklist by the hyaline grass bug, cotton bollworm, spider mite-related records represented by the carmine spider mite, aphid-related records represented by the corn leaf aphid, rice leaf folder, and mole cricket-related records represented by the single-spined mole cricket. These pest variables are consistent with previous reports that millet fields may be affected by stem borers, leaf-feeding insects, shoot flies, sucking pests, and other insect pest groups [13,14,28–30]. Most insect pests were recorded using the insect infestation rate. Double-spotted long-tarsed leaf beetle and stink bug-related records were recorded using insect abundance per plant.

The disease and pest nomenclature followed the revised disease–pest checklist for the monitoring dataset. For records originally recorded at the group level, such as stink bugs, spider mites, aphids, and mole crickets, the group-level category was retained for analysis. Representative species names were used when available in the revised monitoring checklist, to improve consistency in data analysis and figure labeling. Specifically, the hyaline grass bug was used as the representative label for stink bug-related records, the carmine spider mite for spider mite-related records; the corn leaf aphid for aphid-related records, and the single-spined mole cricket for mole cricket-related records. However, these representative names should not be interpreted as laboratory-confirmed or specimen-confirmed species-level identification for all corresponding field records. Representative scientific names and abbreviated monitoring-variable labels in figures are listed in Table A1.

2.4. Data Cleaning and Standardization

The raw monitoring data were checked and standardized before analysis. Province names were unified, each survey site was assigned a unique site identifier, and the original province, city, county, or district, township, or village, and monitoring station information were retained.

Many disease and pest records were expressed as categorical intervals or qualitative descriptions. To allow quantitative summary and comparison, these records were converted into numerical values using interval midpoints. This pragmatic transformation follows the common treatment of grouped or interval data, in which class midpoints can be used as approximate numerical values when exact observations are unavailable [47]. The purpose of this conversion was to obtain semi-quantitative indicators that could be compared among sites and regions, rather than to treat the converted values as exact measurements of disease incidence, pest infestation rate, or insect abundance. Records of no occurrence were coded as absence, with occurrence status assigned as 0, and the numerical value assigned as 0. Records of sporadic or light occurrence below 1% were coded as presence, with occurrence status assigned as 1 and the numerical value assigned as 0.5. Records of light damage without the need for control, corresponding to an infestation or infected-plant rate of

1–5%, were treated as low-level occurrences and converted according to the midpoint rule. Percentage intervals and insect abundance intervals were converted to their midpoints. Blank cells in the original monitoring table were treated as missing values rather than zero values. Detailed transformation rules for categorical records are provided in the Supplementary Materials as Table S1.

2.5. Analysis of Disease and Pest Occurrence Spectrum

To characterize the occurrence spectrum of major diseases and insect pests in foxtail millet, the number of effective survey sites, the number of missing sites, the number of occurrence sites, the occurrence rate, the mean occurrence intensity, the mean occurrence intensity among positive sites, and the maximum value were calculated for each disease and pest. The occurrence rate of a given disease or insect pest was calculated as follows:

$$O_i = \frac{N_{occ,i}}{N_{eff,i}} \times 100 \quad (1)$$

where O_i is the occurrence rate of the i -th disease or insect pest, $N_{occ,i}$ is the number of occurrence sites, and $N_{eff,i}$ is the number of effective survey sites.

For diseases, a site was defined as positive when disease incidence was greater than 0 or when light occurrence was recorded. For insect pests, a site was defined as positive when the insect infestation rate or insect abundance per plant was greater than 0 or when light occurrence was recorded. Effective survey sites excluded missing records for the corresponding disease or pest variable. Two mean values were calculated for each disease or pest: the overall mean based on all effective sites and the positive-site mean based only on occurrence sites.

2.6. Regional Comparison of Disease and Pest Composition

To examine regional differences in disease and pest composition, all survey sites were grouped into the North China–Huang-Huai region, Northeast China, and the Northwest dryland region. The dominant diseases and insect pests in each region were identified based on occurrence counts and proportional contribution to total regional occurrence events. Disease composition was calculated using occurrence records of the nine disease incidence variables. Pest composition was calculated using occurrence records of the twelve insect pest variables. The proportional contribution of each disease or pest was calculated as the number of occurrence events for that disease or pest divided by the total number of disease or pest occurrence events in the corresponding region. Therefore, these percentages represent occurrence-event proportions rather than site-level occurrence rates.

2.7. Disease and Pest Richness

Disease richness, pest richness, and total disease–pest richness were calculated for each survey site to quantify the number of disease and insect pest types recorded at the site level. Disease richness was defined as the number of diseases occurring at a given site. Pest richness was defined as the number of insect pests occurring at a given site. Total disease–pest richness was calculated as the sum of disease richness and pest richness.

$$R_{D,j} = \sum_{i=1}^9 D_{ij} \quad (2)$$

$$R_{P,j} = \sum_{k=1}^{12} P_{kj} \quad (3)$$

$$R_{T,j} = R_{D,j} + R_{P,j} \quad (4)$$

where $R_{D,j}$, $R_{P,j}$, and $R_{T,j}$ represent disease richness, pest richness, and total disease–pest richness at survey site j , respectively. D_{ij} indicates whether the i -th disease occurred at

survey site j , with 1 indicating occurrence and 0 indicating no occurrence. P_{kj} indicates whether the k -th insect pest occurred at survey site j , with 1 indicating occurrence and 0 indicating no occurrence.

Disease richness, pest richness, and total disease–pest richness were calculated from binary presence–absence variables. These indices were used to describe the occurrence breadth of disease and pest categories at each survey site. They indicate how many disease or pest types were recorded, but they do not incorporate occurrence intensity, disease severity, pest abundance, economic damage, or yield loss. Therefore, richness values should be interpreted as descriptive indicators of disease–pest occurrence breadth rather than direct measures of biological damage or management priority.

2.8. Construction of Relative Disease and Pest Pressure Indices

To evaluate integrated disease and pest pressure across survey sites, three relative composite indices were constructed: the disease pressure index, the pest pressure index, and the total disease–pest pressure index. Composite and multivariate indicators are commonly used to summarize complex ecological and biological datasets across multiple variables [48,49]. Because disease incidence, insect infestation rate, and insect abundance per plant had different scales and units, each disease or pest variable was first normalized using min–max standardization. Equal weighting was used when averaging standardized variables because validated organism-specific weights based on yield loss, economic damage, or expert scoring were not available for all monitored diseases and pests. Therefore, these indices were designed as exploratory relative indicators for internal comparison among sites and regions, rather than validated biological damage indices, yield-loss indices, or management thresholds.

$$Z_{ij} = \frac{X_{ij} - X_{i,\min}}{X_{i,\max} - X_{i,\min}} \quad (5)$$

where Z_{ij} is the standardized value of variable i at survey site j , X_{ij} is the original numerical value, and $X_{i,\min}$ and $X_{i,\max}$ are the minimum and maximum values of variable i across all effective survey sites, respectively. If a variable had no variation across effective survey sites, that is, $X_{i,\max} - X_{i,\min}$, it was treated as a zero-variance variable and excluded from the corresponding composite pressure index calculation to avoid division by zero. Therefore, only variables with non-missing values and non-zero ranges were included when calculating site-level pressure indices.

After standardization, the disease pressure index at each survey site was calculated as the mean of standardized disease incidence values across all valid disease variables:

$$I_{D,j} = \frac{\sum_{i=1}^{n_{D,j}} Z_{ij}^D}{n_{D,j}} \quad (6)$$

The pest pressure index was calculated as the mean of standardized pest variables, including insect infestation rate or insect abundance per plant:

$$I_{P,j} = \frac{\sum_{k=1}^{n_{P,j}} Z_{kj}^P}{n_{P,j}} \quad (7)$$

The total disease–pest pressure index was calculated as the mean of all valid standardized disease and pest variables:

$$I_{T,j} = \frac{\sum_{i=1}^{n_{D,j}} Z_{ij}^D + \sum_{k=1}^{n_{P,j}} Z_{kj}^P}{n_{D,j} + n_{P,j}} \quad (8)$$

where $I_{D,j}$, $I_{P,j}$, and $I_{T,j}$ represent the disease pressure index, pest pressure index, and total disease–pest pressure index at survey site j , respectively. Z_{ij}^D and Z_{kj}^P are standardized disease and pest variables, respectively. $n_{D,j}$ and $n_{P,j}$ are the numbers of valid disease and pest variables at survey site j , respectively. $n_{D,j}$ and $n_{P,j}$ are the numbers of disease and pest variables, respectively, with non-missing values and non-zero ranges at survey site j .

Disease severity records for foxtail millet blast and foxtail millet rust were used as supplementary descriptive variables but were not included in the main disease pressure index. This decision was made for two reasons. First, severity data were available only for blast and rust, whereas the main disease pressure index was intended to compare all nine monitored diseases using a consistent incidence-based framework. Second, including both incidence and severity for blast and rust would have given these two diseases greater weight than the other diseases and could have distorted the composite index. Nevertheless, excluding severity information may reduce the epidemiological detail captured by the disease pressure index, and this limitation is acknowledged in the Discussion. These pressure indices were relative composite indicators designed for internal comparison among survey sites and regions in this study. They were not intended to represent official disease severity indices, economic injury levels, or control thresholds, which are usually developed through crop-specific economic and management studies [36].

2.9. Classification Criteria and Sensitivity Analysis

To characterize the overall disease–pest occurrence pattern at each survey site, sites were classified into four disease–pest complex types based on the total disease–pest pressure index and the relative balance between disease pressure and pest pressure. First, sites in the lowest quartile of the total disease–pest pressure index were classified as the low-occurrence type. In this dataset, the first quartile of the total disease–pest pressure index was 0.0648. Among the remaining sites, the ratio between the disease pressure index and the pest pressure index was calculated. Sites with a disease-to-pest pressure ratio greater than 1.15 were classified as the disease-dominated type. Sites with a ratio lower than 0.85 were classified as the pest-dominated type. Sites with a ratio between 0.85 and 1.15 were classified as the disease–pest complex type. The 0.85–1.15 interval was used as a $\pm 15\%$ tolerance range to avoid over-interpreting minor numerical differences between disease pressure and pest pressure. In other words, only sites where one pressure index exceeded the other by more than approximately 15% were classified as dominated by diseases or pests, whereas sites within this tolerance range were regarded as relatively balanced.

To evaluate whether the classification was strongly affected by this empirical tolerance range, a sensitivity analysis was conducted using two alternative tolerance ranges: 0.90–1.10 and 0.80–1.20. The low-occurrence type was kept unchanged based on the lowest quartile of the total disease–pest pressure index, and only the ratio-based classification of the remaining sites was recalculated under the alternative thresholds. The resulting classification counts are provided in Table S9. The low-occurrence type referred to sites with low overall disease and pest pressure, whereas the disease-dominated type referred to sites where disease pressure was clearly higher than pest pressure. The pest-dominated type referred to sites where pest pressure was clearly higher than disease pressure. The disease–pest complex type referred to sites where disease pressure and pest pressure were relatively balanced and both contributed to the overall disease–pest pressure. This classification was used to summarize differences in relative disease–pest pressure structure among survey sites and to support monitoring-oriented interpretation. It should not be interpreted as a biological threshold, economic injury level, or direct field control recommendation.

2.10. Co-Occurrence Analysis of Diseases and Insect Pests

To examine co-occurrence relationships among diseases and insect pests, the occurrence status of each disease and pest was converted into a binary variable, with 1 indicating occurrence and 0 indicating no occurrence. A total of 21 binary variables, including nine diseases and twelve insect pests, were included in the co-occurrence analysis. This binary occurrence-based approach is commonly used in ecological and categorical data analysis to summarize pairwise associations among occurrence variables [41,45].

Pearson correlation analysis was performed on the binary occurrence matrix. Because all variables were binary, the Pearson correlation coefficients can be interpreted as phi correlation coefficients [45]. Positive correlations indicate a tendency for two diseases or pests to co-occur. Negative correlations indicate that two variables were less likely to occur together. Because 210 pairwise tests were conducted, the Benjamini–Hochberg false discovery rate method was used to adjust the p -values [44]. Strong positive co-occurrence pairs were defined as pairs with a correlation coefficient of ($r \geq 0.50$) and an FDR-adjusted ($p < 0.05$). Co-occurrence relationships were interpreted as exploratory statistical associations only. They were not considered evidence of direct causal relationships, biological interactions, vectoring relationships, or shared epidemiological mechanisms, in line with recommended caution in interpreting co-occurrence networks and association patterns [41–43].

2.11. Statistical Analysis and Mapping

Data cleaning and preliminary data organization were conducted using WPS Office Spreadsheets 12.1.0.26895 (Kingsoft Office Software, Beijing, China). Descriptive statistical analyses and nonparametric tests were performed using SPSSAU, an online statistical analysis platform (Version 26.0; The SPSSAU Project, 2026; <https://www.spssau.com>). Descriptive statistics were used to summarize the occurrence rate, mean value, positive-site mean, and maximum value of each disease and insect pest. Regional differences in disease richness, pest richness, total disease–pest richness, disease pressure index, pest pressure index, and total disease–pest pressure index were analyzed using the Kruskal–Wallis nonparametric test because normality could not be assumed [49,50]. A significance level of $p < 0.05$ was used to determine statistical significance.

Statistical charts were prepared using Origin 2021 (OriginLab Corporation, Northampton, MA, USA). Provincial-level spatial maps were prepared using ArcMap 10.8 in ArcGIS Desktop (Esri, Redlands, CA, USA) based on joined provincial attribute tables. The base map was obtained from the standard map service of the Ministry of Natural Resources of China, approval number GS(2023)2767, with no modifications to the base map boundaries. Because the exact geographic coordinates of individual survey sites were not available, spatial visualization was conducted at the provincial scale by aggregating site-level records within each province. Gray areas indicate non-surveyed provinces. Co-occurrence relationships among diseases and insect pests were visualized using a correlation heatmap. The provincial GIS attribute table used for spatial mapping is provided in Table S8.

3. Results

3.1. Overview of Survey Sites

A total of 84 valid survey sites were included in this study. These sites covered 11 provincial-level regions in northern China and were grouped into three broad regions: the North China–Huang-Huai region, Northeast China, and the Northwest dryland region. The North China–Huang-Huai region included Henan, Hebei, Shanxi, and Shandong, with 46 survey sites, accounting for 54.76% of all sites. Northeast China included Liaoning, Jilin, and Heilongjiang, with 19 sites, accounting for 22.62%. The Northwest dryland region

included Inner Mongolia, Gansu, Ningxia, and Shaanxi, also with 19 sites, accounting for 22.62%. The provincial distribution of the monitored regions is shown in Figure 1.



Figure 1. Provincial distribution of foxtail millet disease and insect pest monitoring regions across northern China in 2025. Different colors indicate the three broad monitoring regions included in this study: the North China–Huang-Huai region, Northeast China, and the Northwest dryland region. Gray areas indicate non-surveyed provinces. The base map was obtained from the standard map service of the Ministry of Natural Resources of China, approval number GS(2023)2767, with no modifications to the base map boundaries.

The regional distribution and basic characteristics of the survey sites are summarized in Table 1.

As shown in Table 1, Northeast China had the highest mean total disease–pest richness, with an average value of 12.05. This value consisted of a mean disease richness of 6.26 and a mean pest richness of 5.79. The North China–Huang-Huai region had a mean total richness of 9.11, whereas the Northwest dryland region had the lowest value, at 8.16. These descriptive results suggest that survey sites in Northeast China more frequently harbored multiple disease and pest types at the same time.

Table 1. Regional distribution and basic characteristics of foxtail millet disease and pest survey sites in 2025.

Region	Included Provincial-Level Regions	Number of Sites	Proportion (%)	Mean Disease Richness	Mean Pest Richness	Mean Total Richness
North China–Huang-Huai region	Henan, Hebei, Shanxi, Shandong	46	54.76	4.11	5.00	9.11
Northeast China	Liaoning, Jilin, Heilongjiang	19	22.62	6.26	5.79	12.05
Northwest dryland region	Inner Mongolia, Gansu, Ningxia, Shaanxi	19	22.62	3.79	4.37	8.16
Total	11 provincial-level regions	84	100.00	4.52	5.04	9.56

3.2. Occurrence Spectrum of Major Diseases and Insect Pests

The occurrence spectrum showed that multiple diseases and insect pests were recorded in foxtail millet fields at the grain-filling stage in 2025. Complete occurrence statistics for the nine diseases and twelve insect pests are provided in Tables S2 and S3, respectively. To facilitate comparison, occurrence rates of major diseases and insect pests were visualized in Figure 2.

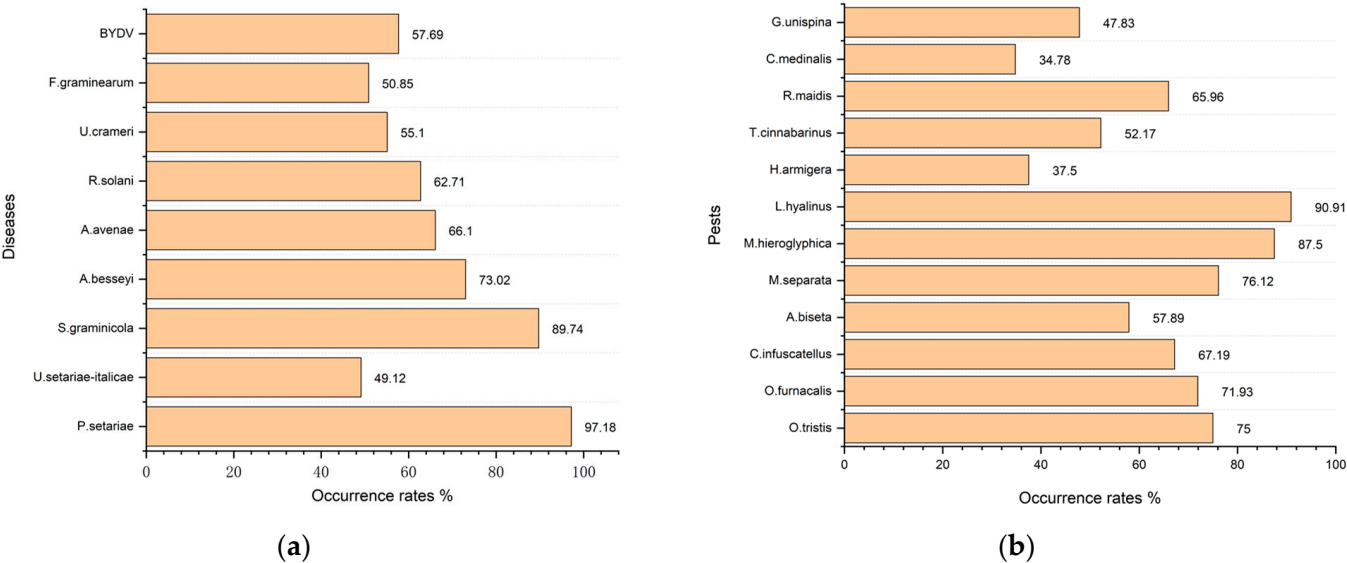


Figure 2. Occurrence rates of major diseases and insect pests in foxtail millet in 2025. (a) Occurrence rates of major diseases. (b) Occurrence rates of major insect pests. Occurrence rates were calculated based on the number of occurrence sites and effective survey sites. To improve figure readability, abbreviated checklist-associated scientific names or representative labels listed in Table A1 are used in the figure. Disease records were based on expert field diagnosis and should not be interpreted as laboratory-confirmed pathogen records. Pest records were based on expert field identification or pest-group monitoring records. For pest variables originally recorded at the group level, such as stink bugs, spider mites, aphids, and mole crickets, group-level categories were retained in the analysis. Representative species names were used only for consistency with the revised monitoring checklist and figure labeling and should not be interpreted as specimen-confirmed species-level occurrence records.

Among the nine monitored diseases, foxtail millet blast, millet downy mildew, and foxtail millet sheath blight were the most prominent. Foxtail millet blast occurred at

69 of 71 effective sites, with the highest occurrence rate of 97.18%. Its mean disease incidence was 10.17%, and the maximum disease incidence reached 90.00%. These results indicate that foxtail millet blast was both widely distributed and locally severe. Millet downy mildew occurred at 70 of 78 effective sites, with an occurrence rate of 89.74%. Its mean disease incidence was 3.18%, suggesting broad distribution but generally low intensity. Foxtail millet sheath blight occurred at 73.02% of effective sites, with a mean disease incidence of 5.12% and a maximum value of 90.00%, indicating severe occurrence at some sites.

Among insect pests, stink bug-related records represented by the hyaline grass bug and double-spotted long-tarsed leaf beetle records, stink bug-related records were the most frequently recorded, with occurrence rates of 90.91% and 87.50%, respectively. Their maximum recorded abundance reached 30.00 individuals per plant. Among pests recorded by infestation rate, armyworm had the highest occurrence rate, at 76.12%, with a mean infestation rate of 4.29% and a maximum value of 30.00%. Foxtail millet leaf beetle and Asian corn borer also occurred frequently, with occurrence rates of 75.00% and 71.93%, respectively. Overall, the disease and pest spectrum at the grain-filling stage was characterized by the widespread occurrence of foxtail millet blast, millet downy mildew, stink bug-related records represented by the stink bug-related records, double-spotted long-tarsed leaf beetle records, armyworm, foxtail millet leaf beetle, and Asian corn borer, together with localized severe occurrence of several diseases and pests.

3.3. Regional Differences in Disease–Pest Composition, Richness, and Relative Pressure

Disease and pest composition differed among the three regions. The dominant diseases and insect pests in each region were identified based on their proportional contributions to total disease or pest occurrence events. Detailed regional composition results are provided in Table S4. In the North China–Huang-Huai region, disease occurrence events were mainly represented by foxtail millet blast and millet downy mildew. The pest composition was relatively dispersed among armyworms records, double-spotted long-tarsed leaf beetles records, millet stem borers records, stink bug-related records, and foxtail millet leaf beetles records. In Northeast China, both disease and pest composition were more diverse. In the Northwest dryland region, disease composition was more concentrated, with millet downy mildew and foxtail millet blast together accounting for a large proportion of disease occurrence events.

To compare disease and pest richness and pressure among regions, disease richness, pest richness, total disease–pest richness, disease pressure index, pest pressure index, and total disease–pest pressure index were calculated at the site level. Because normality could not be assumed, regional differences were tested using the Kruskal–Wallis nonparametric test [49,50]. The results are shown in Table 2.

The regional distributions of the disease pressure index, pest pressure index, and total disease–pest pressure index were further visualized using boxplots, as shown in Figure 3.

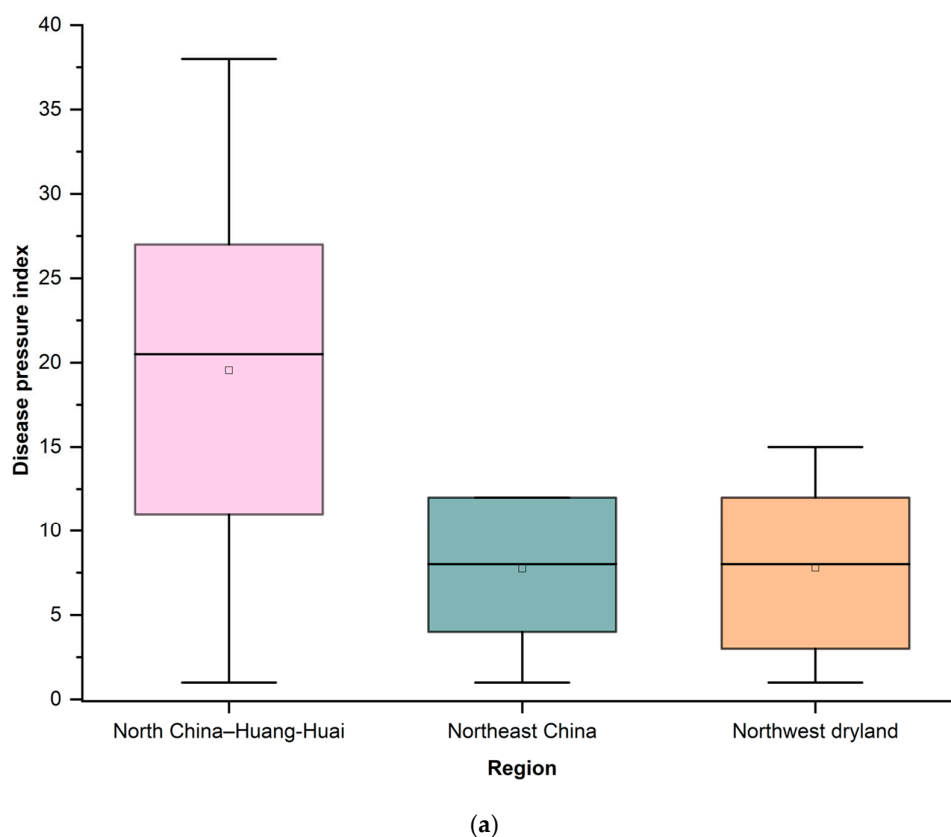
As shown in Table 2, disease richness differed significantly among regions ($H = 14.482$, $p = 0.001$). Northeast China had the highest median disease richness, with a value of 6.000, compared with 4.000 in both the North China–Huang-Huai region and the Northwest dryland region. Total disease–pest richness also differed significantly among regions ($H = 8.553$, $p = 0.014$), with Northeast China showing the highest median value. In contrast, pest richness did not differ significantly among regions ($H = 3.550$, $p = 0.170$).

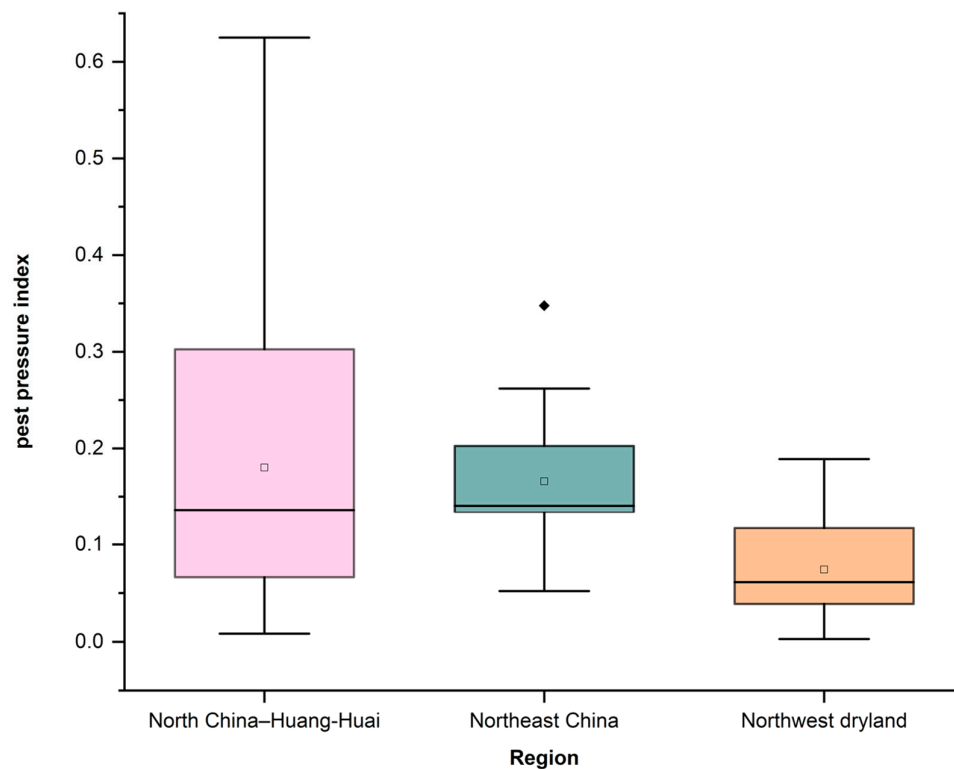
Table 2. Regional comparison of disease–pest richness and relative pressure indices.

Variable	Northeast China, <i>n</i> = 19	North China–Huang-Huai Region, <i>n</i> = 46	Northwest Dryland Region, <i>n</i> = 19	H Value	<i>p</i> -Value
Disease richness	6.000 (5.000, 8.000)	4.000 (2.000, 6.000)	4.000 (2.000, 5.000)	14.482	0.001 **
Pest richness	6.000 (3.000, 7.000)	4.000 (3.000, 7.000)	3.000 (2.000, 7.000)	3.550	0.170
Total disease–pest richness	13.000 (8.000, 14.000)	8.000 (5.000, 13.000)	8.000 (4.000, 12.000)	8.553	0.014 *
Disease pressure index	0.135 (0.082, 0.224)	0.060 (0.029, 0.150)	0.057 (0.031, 0.127)	7.925	0.019 *
Pest pressure index	0.140 (0.133, 0.202)	0.136 (0.065, 0.304)	0.061 (0.039, 0.117)	12.709	0.002 **
Total disease–pest pressure index	0.120 (0.103, 0.220)	0.127 (0.052, 0.223)	0.077 (0.039, 0.104)	11.219	0.004 **

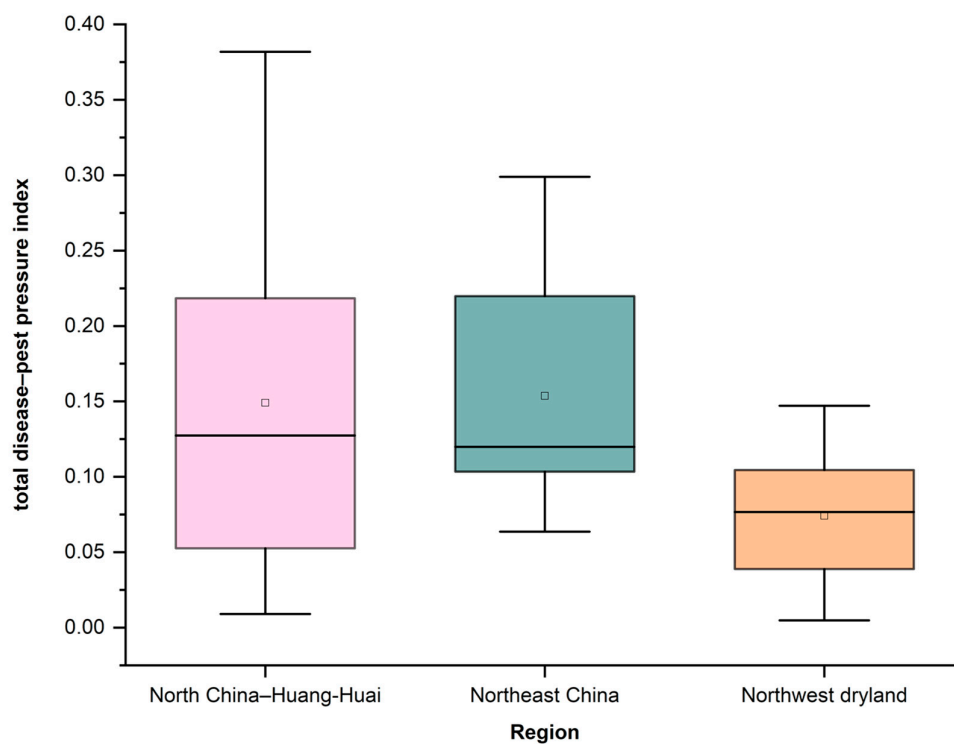
Note: Values are medians with interquartile ranges, M (P25, P75). Regional differences were tested using the Kruskal–Wallis test [50]. * ($p < 0.05$); ** ($p < 0.01$).

As shown in Table 2 and Figure 3, the disease pressure index differed significantly among regions ($H = 7.925$, $p = 0.019$), with Northeast China showing the highest median value. The pest pressure index also differed significantly among regions ($H = 12.709$, $p = 0.002$). Northeast China and the North China–Huang-Huai region had similar pest pressure indices, both higher than that of the Northwest dryland region. The total disease–pest pressure index differed significantly among regions ($H = 11.219$, $p = 0.004$), with the North China–Huang-Huai region and Northeast China showing higher values than the Northwest dryland region. These results demonstrate clear regional differentiation in disease–pest composition and relative pressure.

**Figure 3.** Cont.



(b)



(c)

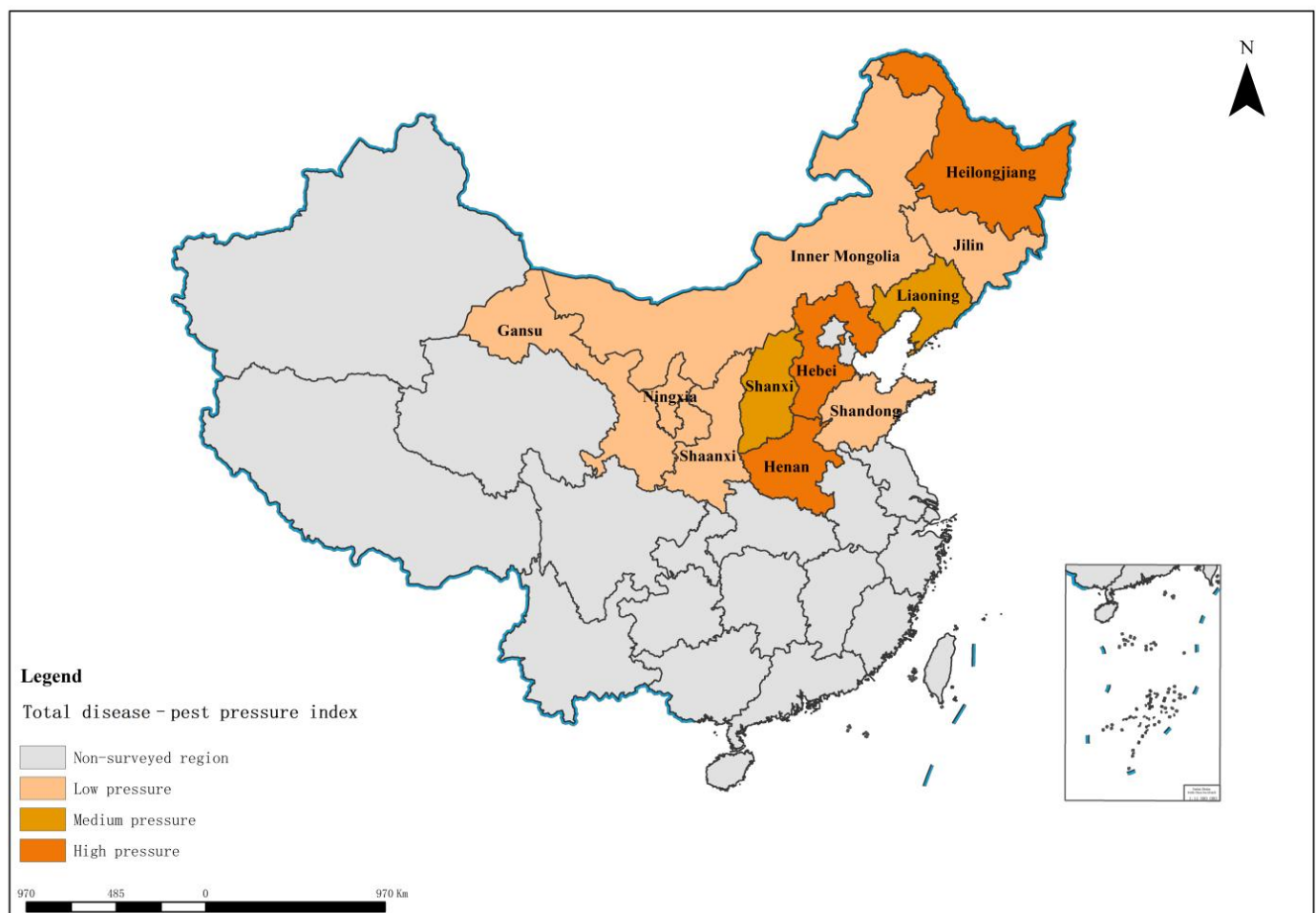
Figure 3. Comparison of disease and pest pressure indices among regions. (a) Disease pressure index. (b) Pest pressure index. (c) Total disease–pest pressure index. Boxes represent interquartile ranges; horizontal lines represent medians, and whiskers extend to the most extreme values within 1.5 times the interquartile range from the lower and upper quartiles. Points beyond the whiskers are shown as outliers.

3.4. Provincial Spatial Patterns of Disease–Pest Pressure and Complex Types

To visualize spatial variation at the provincial scale, site-level total disease–pest pressure indices were aggregated within each province. The dominant disease–pest complex type in each province was determined according to the most frequent site-level type. The provincial distribution of the mean total disease–pest pressure index and dominant disease–pest complex types is shown in Figure 4.

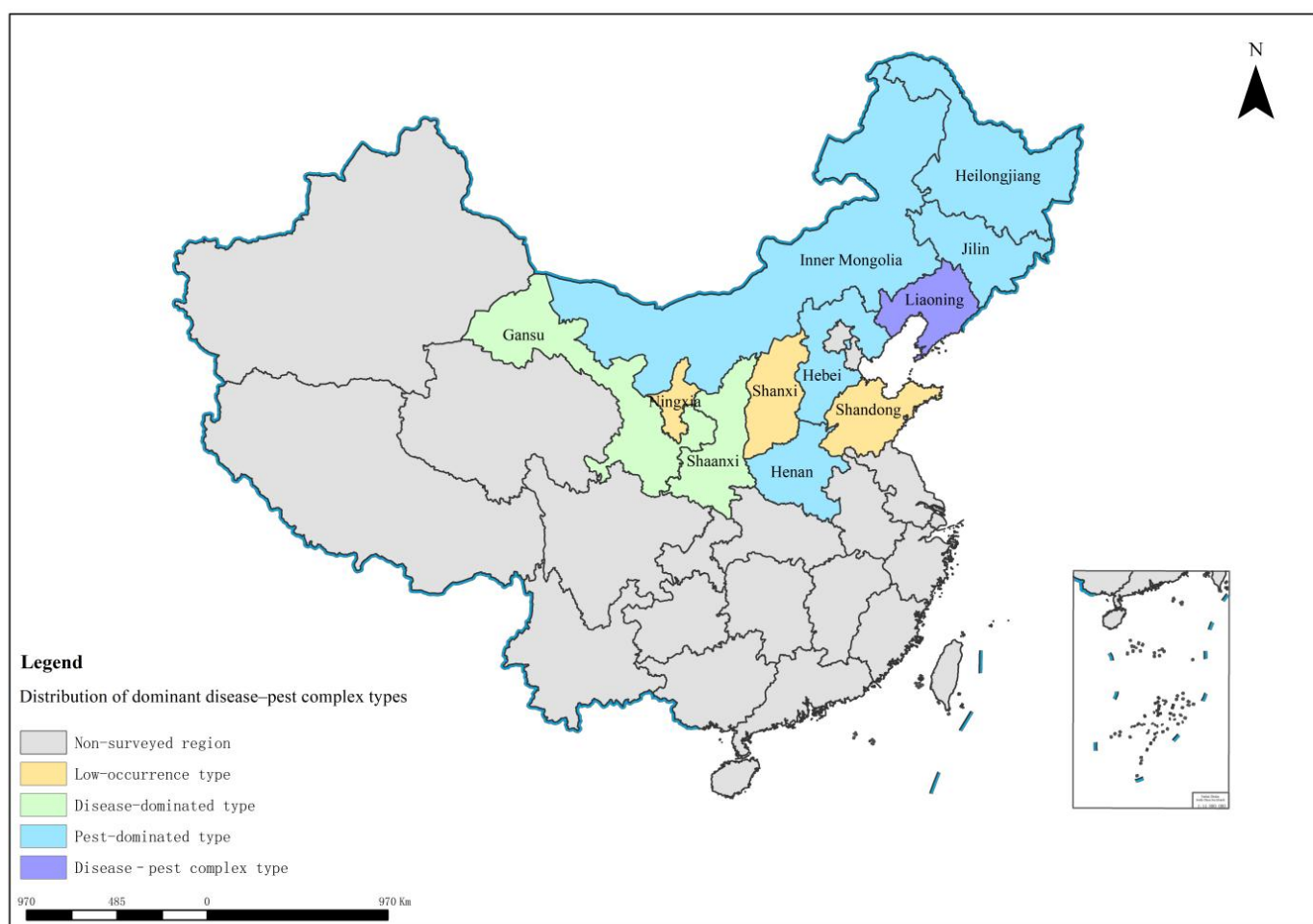
Based on the provincial mean total disease–pest pressure index, Liaoning, Heilongjiang, Hebei, and Henan were classified as high-pressure provinces. Jilin, Shanxi, and Inner Mongolia were classified as medium-pressure provinces, whereas Shandong, Gansu, Ningxia, and Shaanxi were classified as low-pressure provinces. High-pressure provinces were distributed mainly in Northeast China and the North China–Huang-Huai region. However, the provincial classifications should be interpreted descriptively because the number of survey sites differed among provinces. In particular, Gansu included only one survey site, and its provincial classification should therefore be interpreted with caution.

The provincial map of the mean total disease–pest pressure index revealed spatial heterogeneity among the monitored provincial-level regions. The distribution of dominant complex types further showed that disease–pest pressure structure differed among provinces. These spatial patterns support the classification-based interpretation of disease–pest occurrence and provide a provincial-scale visualization of pressure structure across northern China.



(a)

Figure 4. Cont.



(b)

Figure 4. Provincial distribution of total disease–pest pressure and dominant disease–pest complex types in foxtail millet across northern China in 2025. (a) Provincial distribution of the mean total disease–pest pressure index. (b) Provincial distribution of dominant disease–pest complex types. Gray areas indicate non-surveyed provinces. The base map was obtained from the standard map service of the Ministry of Natural Resources of China, approval number GS(2023)2767, with no modifications to the base map boundaries.

3.5. Classification of Disease–Pest Complex Types

Based on the disease pressure index, pest pressure index, and total disease–pest pressure index, the 84 survey sites were classified into four disease–pest complex types: the low-occurrence type, the disease-dominated type, the pest-dominated type, and the disease–pest complex type. The number and regional distribution of these complex types are shown in Table 3. Richness and pressure characteristics of different complex types are provided in Table S5.

The regional composition of disease–pest complex types was further compared among the three broad regions, as shown in Figure 5.

Different colors represent low-occurrence, disease-dominated, pest-dominated, and disease–pest complex types. Bars show the proportion of each complex type within each region. The y-axis represents percentage composition and ranges from 0 to 100%. The pest-dominated type was the most common, including 40 sites and accounting for 47.62% of all survey sites. The low-occurrence type included 21 sites, accounting for 25.00%, whereas the disease-dominated type included 16 sites, accounting for 19.05%. The disease–pest complex type was the least frequent, with 7 sites, accounting for 8.33%.

Table 3. Number and regional distribution of disease–pest complex types.

Complex Type	Total Sites	Proportion (%)	North China–Huang-Huai Region	Northeast China	Northwest Dryland Region	Main Feature
Low-occurrence type	21	25.00	14	1	6	Low disease and pest pressure
Disease-dominated type	16	19.05	6	5	5	Disease pressure higher than pest pressure
Pest-dominated type	40	47.62	23	11	6	Pest pressure higher than disease pressure
Disease–pest complex type	7	8.33	3	2	2	Disease and pest pressure relatively balanced
Total	84	100.00	46	19	19	—

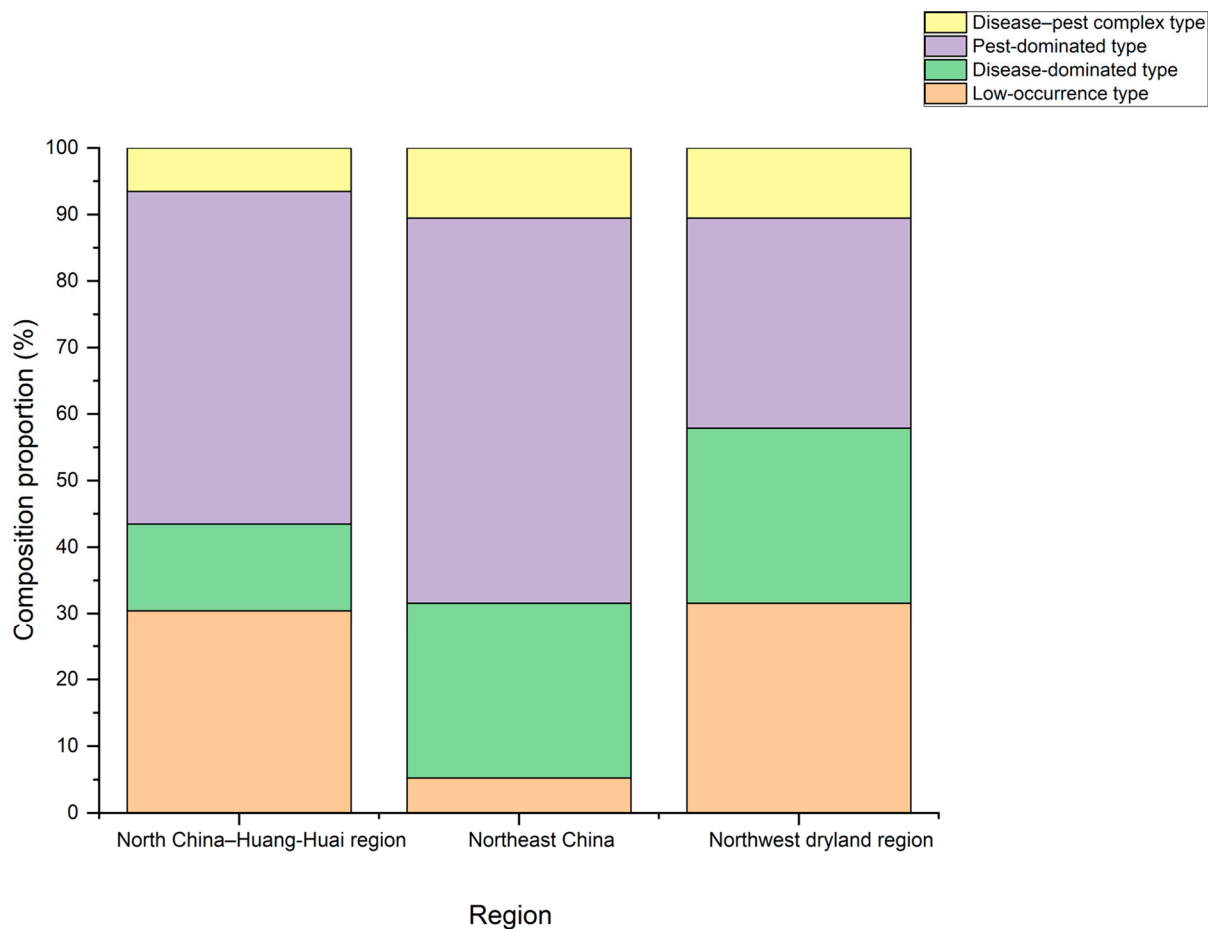


Figure 5. Composition of disease–pest complex types among regions.

In the North China–Huang-Huai region, the pest-dominated type and the low-occurrence type were the two major categories, accounting for 50.00% and 30.43% of regional sites, respectively. In Northeast China, the pest-dominated type was also dominant, accounting for 57.89% of regional sites. The Northwest dryland region showed a more dispersed distribution of complex types, with low-occurrence and pest-dominated types each accounting for 31.58% of regional sites. These results indicate that pest-dominated occurrence was the most frequent disease–pest pressure structure in the 2025 survey dataset. Provincial and regional differences in complex types further suggest that disease–pest

pressure structure varied among regions and should be interpreted together with local occurrence profiles.

3.6. Co-Occurrence Patterns Among Diseases and Insect Pests

Co-occurrence relationships among the 21 diseases and insect pests were analyzed using binary occurrence variables. Because these variables were binary, the correlation coefficients can be interpreted as phi correlation coefficients [45]. Strong positive co-occurrence pairs were defined as pairs with correlation coefficients of $r \geq 0.50$ and FDR-adjusted $p < 0.05$, following false discovery rate correction for multiple pairwise tests [44]. Representative strong co-occurrence pairs are shown in Table 4, and the complete list is provided in Table S6.

Table 4. Representative strong positive co-occurrence pairs among field-diagnosed disease categories and insect pest variables.

Type	Disease Category or Pest Variable Pair	Correlation Coefficient, r	FDR-Adjusted p -Value
Disease–disease	Bacterial leaf stripe of millet—foxtail millet ear rot	0.699	<0.05
Disease–disease	Millet downy mildew—foxtail millet sheath blight	0.650	<0.05
Disease–disease	Foxtail millet sheath blight—red leaf disease	0.565	<0.05
Pest–pest	Double-spotted long records-tarsed leaf beetle—stink bug-related records	0.822	<0.05
Pest–pest	Cotton bollworm records—single-spined mole cricket records	0.671	<0.05
Pest–pest	Asian corn borer records—millet stem borer records	0.650	<0.05
Disease–pest	Millet downy mildew—stink bug-related records	0.826	<0.05
Disease–pest	Foxtail millet nematode disease—millet shoot fly records	0.703	<0.05
Disease–pest	Millet downy mildew—double-spotted long-tarsed leaf beetle records	0.672	<0.05

Note: Representative positive co-occurrence pairs with ($r \geq 0.50$) and FDR-adjusted ($p < 0.05$) are shown. The complete list of strong positive co-occurrence pairs is provided in Table S6. Occurrence status was represented by binary variables derived from the field-monitoring records. Because the variables were binary, the correlation coefficients can be interpreted as phi correlation coefficients [45]. For group-level pest records, such as stink bugs and mole crickets, group-level categories were retained in the analysis and should not be interpreted as specimen-confirmed species-level occurrence records.

To visualize the overall pairwise association structure among diseases and insect pests, a co-occurrence correlation heatmap was generated based on the binary occurrence matrix (Figure 6). Complete pairwise correlation results are provided in Table S7.

As shown in Table 4 and Figure 6, several strong positive associations were detected among disease–disease, pest–pest, and disease–pest pairs. Among disease–disease pairs, bacterial leaf stripe of millet and foxtail millet ear rot showed the strongest positive association, with $r = 0.699$. Millet downy mildew and foxtail millet sheath blight also showed a strong positive association, with $r = 0.650$. Among pest–pest pairs, double-spotted long-tarsed leaf beetle records and stink bug-related records showed the strongest association, with $r = 0.822$. The Asian corn borer was also involved in several strong associations with other insect pest variables.

Strong disease–pest associations were also observed. Millet downy mildew and stink bug-related records showed the highest correlation among all disease–pest pairs, with $r = 0.826$. Millet downy mildew was also positively associated with double-spotted long-tarsed leaf beetle records, armyworm records, millet stem borer records, and Asian corn borer records. Other notable disease–pest associations included foxtail millet nematode disease–millet shoot fly records, foxtail millet sheath blight–armyworm records, red leaf disease–Asian corn borer records, and foxtail millet ear rot–Asian corn borer records. Overall, foxtail millet diseases and insect pest variables exhibited clear co-occurrence

patterns in the 2025 grain-filling-stage monitoring dataset. These associations should be interpreted as statistical co-occurrence rather than causal relationships, but they identify disease–pest combinations that may warrant future joint surveillance and hypothesis-driven investigation [41–43].

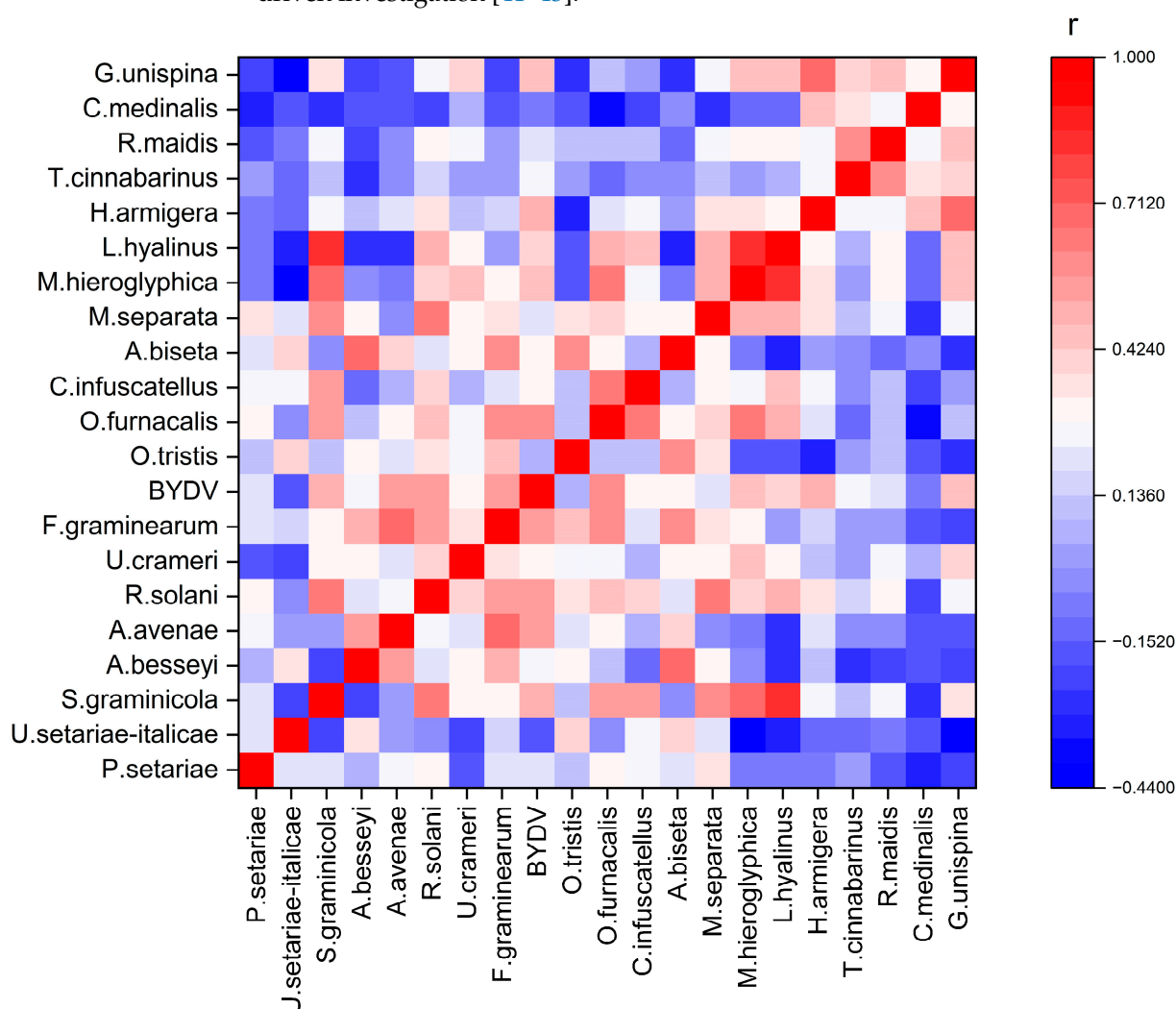


Figure 6. Co-occurrence correlation heatmap of field-diagnosed disease categories and insect pest variables in foxtail millet. Colors represent correlation coefficients calculated from binary occurrence variables. Positive values indicate co-occurrence tendencies, whereas negative values indicate lower co-occurrence tendencies. Strong significant co-occurrence pairs are summarized in Table 4 and fully listed in Table S6. To improve figure readability, abbreviated monitoring-variable labels listed in Table A1 are used as labels in the figure. For pest variables originally recorded at the group level, such as stink bugs, spider mites, aphids, and mole crickets, group-level categories were retained in the analysis. Representative species names in the revised monitoring checklist were used only for label consistency and should not be interpreted as specimen-confirmed species-level occurrence records.

4. Discussion

4.1. Occurrence Spectrum of Major Diseases and Insect Pests in Foxtail Millet

Using field-monitoring data from 84 survey sites across northern China in 2025, this study characterized the multi-regional occurrence of major diseases and insect pests in foxtail millet. The results showed that foxtail millet fields were affected by multiple diseases and insect pests. This pattern indicates a field-level disease–pest complex rather than pressure from a single dominant biotic stressor. The finding is consistent with previous

reports that millet and foxtail millet production may be affected by diverse diseases and insect pests under both field and controlled conditions [13–16,28–32].

Among the nine monitored diseases, foxtail millet blast, millet downy mildew, and foxtail millet sheath blight were the most prominent. Foxtail millet blast had the highest occurrence rate, reaching 97.18%, and its maximum disease incidence reached 90.00%. These values indicate both broad distribution and severe infection at some sites. This result agrees with previous studies identifying foxtail millet blast as an important disease that requires resistance identification and integrated management [17–19]. Millet downy mildew also occurred widely, with an occurrence rate of 89.74%. However, its mean disease incidence was relatively low, suggesting frequent but generally low-intensity occurrence. Previous studies have shown that *Sclerospora graminicola*, cropping systems, rhizosphere microbial communities, and host resistance are closely associated with millet downy mildew development and suppression [21,22,25,26]. Foxtail millet sheath blight occurred at 73.02% of effective sites, and its maximum disease incidence also reached 90.00%. This result suggests that the disease can develop into severe local outbreaks under favorable field conditions. Biological control studies on banded sheath blight in little millet and foxtail millet further indicate that this disease group is relevant to sustainable disease management [27].

The insect pest spectrum also differed among pest variables. Stink bug-related records represented in the monitoring checklist by the hyaline grass bug and double-spotted long-tarsed leaf beetle records were the most frequently recorded pest variables, with occurrence rates of 90.91% and 87.50%, respectively. Armyworm, foxtail millet leaf beetle, and Asian corn borer also occurred frequently. These results are consistent with previous studies showing that millet production can be affected by stem borers, leaf-feeding insects, shoot flies, sucking pests, and other insect pest groups [13,14,28–30]. Overall, the occurrence spectrum indicates that foxtail millet disease and pest monitoring should not be organized around only one dominant species. Both widely distributed stressors and locally severe diseases or pests need to be considered. In the present dataset, foxtail millet blast, millet downy mildew, foxtail millet sheath blight, stink bug-related records represented by the hyaline grass bug, double-spotted long-tarsed leaf beetle records, armyworm, foxtail millet leaf beetle, and Asian corn borer emerged as priority targets for grain-filling-stage field monitoring [13–17,19,27–33].

4.2. Regional Differentiation and Provincial Spatial Patterns

Disease–pest composition differed among the North China–Huang-Huai region, Northeast China, and the Northwest dryland region. This regional differentiation shows that foxtail millet disease–pest complexes were unevenly distributed across the surveyed regions in 2025. In the North China–Huang-Huai region, disease occurrence was mainly represented by foxtail millet blast and millet downy mildew, whereas pest composition was distributed across several pest groups. In Northeast China, both disease and pest composition were more diverse. In the Northwest dryland region, disease composition was more concentrated, with millet downy mildew and foxtail millet blast accounting for a large proportion of disease occurrence events.

The regional differences observed in this study may be associated with variation in climate, cropping systems, cultivar distribution, sowing date, growth stage, field management, and local ecological conditions. Previous studies have shown that foxtail millet has substantial genetic diversity and local adaptation. Other studies have also reported that cropping systems and rhizosphere microbial communities can influence millet downy mildew suppression [7,8,25,26]. However, the present dataset did not include detailed environmental, cultivar, sowing date, fertilization, pesticide use, or management variables.

Therefore, the drivers of regional differentiation could not be tested directly. The regional patterns identified here should be interpreted as descriptive evidence of disease–pest composition differences in the 2025 grain-filling-stage monitoring dataset, rather than as evidence of specific causal mechanisms.

The construction of disease richness, pest richness, total disease–pest richness, and relative pressure indices allowed disease–pest occurrence to be evaluated from both diversity and intensity perspectives. Composite and multivariate indicators are commonly used in ecological data analysis to summarize complex patterns across multiple variables [48,49]. Northeast China showed the highest disease richness and total disease–pest richness, indicating that survey sites in this region tended to contain more concurrent disease and pest types. For relative pressure, Northeast China and the North China–Huang-Huai region showed higher total disease–pest pressure than the Northwest dryland region. These findings suggest that the North China–Huang-Huai region and Northeast China should receive closer attention in disease–pest monitoring within the scope of the 2025 dataset.

An important observation is that the region with the highest richness was not necessarily the region with the highest total pressure index. Northeast China had the highest total disease–pest richness, whereas the North China–Huang-Huai region showed a slightly higher median total pressure index. This contrast suggests that disease–pest richness and disease–pest pressure represent related but distinct dimensions. A region may contain many disease and pest types at moderate intensity. Conversely, another region may contain fewer types but experience higher pressure from key stressors. Therefore, both richness and pressure indices should be considered when evaluating regional disease–pest risk.

At the provincial scale, the spatial maps further illustrated heterogeneity in total disease–pest pressure and dominant disease–pest complex types among the monitored provinces. Because the exact geographic coordinates of individual survey sites were not available, these maps should be interpreted as provincial-scale descriptive visualizations rather than fine-scale spatial analyses. Nevertheless, they help translate site-level monitoring results into a spatial framework that can support region-specific monitoring and management.

The pressure indices used in this study are relative composite indicators constructed for comparison within the present dataset. They are not equivalent to official disease severity indices, economic thresholds, yield-loss models, or management thresholds. Because equal weights were assigned to all monitored diseases and pests after standardization, the indices assume equal contribution of each variable to the composite pressure score. This assumption was necessary because validated organism-specific weights were unavailable, but it also limits the biological interpretation of the indices. Their main value lies in comparing relative disease–pest pressure among survey sites, regions, and provinces, rather than defining direct control thresholds for field application or estimating actual crop damage [40,48,50].

4.3. Disease–Pest Complex Type Classification and Monitoring Implications

Based on relative disease and pest pressure indices, the 84 survey sites were classified into four complex types: low-occurrence, disease-dominated, pest-dominated, and disease–pest complex types. The pest-dominated type was the most common, accounting for 40 of 84 sites (47.62%). It was followed by the low-occurrence type, which accounted for 21 sites (25.00%), the disease-dominated type, and the disease–pest complex type, which accounted for 7 sites (8.33%). This pattern suggests that insect pest pressure contributed substantially to the overall disease–pest pressure structure in many foxtail millet fields during the 2025 grain-filling-stage survey.

This classification provides a practical framework for interpreting relative disease–pest pressure structure at the site level. The low-occurrence type had relatively low disease richness, pest richness, and total pressure index, suggesting low observed disease–pest pressure within the present dataset. The disease-dominated type had a relatively high disease pressure index, indicating that disease surveillance should receive greater attention at these sites. The pest-dominated type had a relatively high pest pressure index and represented nearly half of all survey sites, indicating that pest monitoring deserves particular attention in foxtail millet fields during the grain-filling stage. The disease–pest complex type showed relatively balanced disease and pest pressure, suggesting that integrated surveillance of both disease and pest variables may be especially important at these sites. However, these interpretations should be viewed descriptive and monitoring-oriented summaries of relative pressure structure, rather than direct control recommendations, because the pressure indices were relative composite indicators and were not validated against yield loss, economic damage, or organism-specific control thresholds.

The classification-based interpretation is broadly consistent with the general principles of integrated pest management, which emphasize field monitoring, site-specific assessment, and decision-making based on pest or disease status [33–36]. However, the classification used in this study should not be interpreted as an official management threshold or economic injury level. Instead, it provides an exploratory framework for distinguishing whether disease pressure, pest pressure, or both contributed more strongly to the overall disease–pest pressure structure at each survey site. Therefore, compared with a simple classification based only on occurrence rate or total pressure, the disease–pest complex type framework can provide additional information on the relative contribution of disease and pest variables to site-level pressure structure. The regional and provincial distribution of complex types further supported the value of classification-based interpretation. The North China–Huang-Huai region and Northeast China were both dominated by pest-dominated sites, indicating that pest occurrence contributed strongly to the overall disease–pest pressure structure in these regions. The Northwest dryland region showed a more dispersed distribution of complex types. Although its overall disease–pest pressure was relatively low, site-level variation still existed. These results suggest that disease and pest monitoring in foxtail millet should not rely only on broad regional averages. Instead, local pressure structure should also be considered when identifying monitoring priorities. Sites classified as pest-dominated may require closer attention to major insect pest variables, whereas disease-dominated sites may require more focused monitoring of major field-diagnosed disease categories. Sites classified as disease–pest complex types may require integrated surveillance of both disease and pest variables.

The threshold-based classification should be interpreted as an analytical tool for summarizing relative disease–pest pressure structure, not as a biological boundary or field control threshold. The 0.85–1.15 range was selected to provide a practical tolerance interval around equal disease and pest pressure and to reduce the risk of assigning dominance based on very small differences between the two relative indices. To evaluate whether the classification was strongly affected by this empirical tolerance range, a sensitivity analysis was conducted using two alternative tolerance ranges, 0.90–1.10 and 0.80–1.20. Under the original 0.85–1.15 tolerance range, the pest-dominated type was the most frequent category, accounting for 40 sites (47.62%). When a narrower tolerance range of 0.90–1.10 was used, the pest-dominated type remained the most frequent category, accounting for 42 sites (50.00%). When a wider tolerance range of 0.80–1.20 was used, the pest-dominated type was still the most frequent category, accounting for 38 sites (45.24%). Only four sites changed classification under the narrower tolerance range, and two sites changed classification

under the wider tolerance range. These changes mainly occurred among sites close to the original threshold boundaries.

Overall, the sensitivity analysis showed that the main classification pattern was generally stable under alternative threshold settings. In particular, the conclusion that pest-dominated sites were the most common type was not solely determined by the selected 0.85–1.15 cut-off values. Nevertheless, the classification of borderline sites should still be interpreted cautiously, because their category assignment may change when alternative tolerance ranges are used. Therefore, the complex-type classification is most useful for identifying broad relative pressure structures, supporting monitoring-oriented interpretation, and informing preliminary monitoring prioritization, rather than for defining strict management thresholds or making direct field control recommendations. Future studies should further refine this classification framework using multi-year datasets, repeated surveys across different crop growth stages, yield-loss information, and independent expert validation.

4.4. Co-Occurrence Patterns and Their Implications for Integrated Monitoring

The co-occurrence analysis revealed several strong positive associations among field-diagnosed disease categories, among insect pest variables, and between disease categories and insect pest variables. Among disease–disease pairs, bacterial leaf stripe of millet and foxtail millet ear rot showed the strongest positive association. Millet downy mildew and foxtail millet sheath blight also showed a strong positive association. These disease–disease associations may reflect shared environmental conditions, similar cultivar susceptibility, common field management practices, or overlapping growth stages favorable for disease development [37,38,41–43]. Among pest–pest pairs, double-spotted long-tarsed leaf beetle records and stink bug-related records showed the strongest association. Asian corn borer was also involved in several strong pest–pest associations, including associations with millet stem borer records, double-spotted long-tarsed leaf beetle records, and stink bug-related records. These relationships indicate that certain insect pest variables tended to be recorded together under similar field conditions. Strong disease–pest associations were also observed. Millet downy mildew was positively associated with several insect pest variables, including stink bug-related records, double-spotted long-tarsed leaf beetle, armyworm records, millet stem borer records, and Asian corn borer records. Other notable disease–pest associations included foxtail millet nematode disease–millet shoot fly records, foxtail millet sheath blight–armyworm records, red leaf disease–Asian corn borer records, and foxtail millet ear rot–Asian corn borer records. These associations indicate that some disease categories and insect pest variables tended to occur at the same survey sites during the 2025 grain-filling-stage survey.

These co-occurrence patterns should be interpreted with particular caution. Significant positive correlations between pairs of diseases, pairs of insect pests, or a disease and an insect pest only indicate that they tended to be recorded at the same survey sites in the 2025 dataset. Such correlations do not necessarily imply direct biological interactions, causal relationships, vectoring relationships, or shared epidemiological mechanisms. The associations may instead result from shared regional environments, cultivar distribution, sowing date, growth stage, field management practices, sampling structure, or other unmeasured factors. Therefore, the main value of co-occurrence analysis in this study is exploratory: it identifies disease–pest combinations that may warrant joint monitoring and future hypothesis-driven investigation, rather than providing direct evidence of interaction or causality [41–43].

For field monitoring, the results suggest that diseases and insect pests should not be recorded completely in isolation. When one member of a strong co-occurrence pair is

detected, the associated disease or pest variable may also need to be checked. Disease and pest combinations such as millet downy mildew–stink bug-related records, double-spotted long-tarsed leaf beetle–stink bug-related records, Asian corn borer records–millet stem borer records, and bacterial leaf stripe of millet–foxtail millet ear rot may serve as candidate combinations for joint field surveillance. For group-level pest records, these combinations should be interpreted at the monitoring-category level rather than as confirmed species-level associations. This approach may improve the detection of disease–pest complexes and support more targeted monitoring decisions. However, these combinations should be validated with multi-year field data before being used for causal interpretation or prediction [33–36,41–43].

From a monitoring perspective, the results suggest that foxtail millet disease and pest surveillance should consider both dominant stressors and disease–pest complexes. Widely distributed field-diagnosed disease categories and insect pest variables, including foxtail millet blast, millet downy mildew, foxtail millet sheath blight, stink bug-related records represented by the hyaline grass bug, double-spotted long-tarsed leaf beetle records, armyworm records, foxtail millet leaf beetle records, and Asian corn borer records, should be prioritized in routine field monitoring during the grain-filling stage. Regional differences in richness and relative pressure also indicate that monitoring intensity should be adjusted according to local disease–pest profiles. In the North China–Huang-Huai region and Northeast China, where total disease–pest pressure was relatively high, closer field scouting may be needed during key growth stages. The complex-type classification may further support site-specific monitoring prioritization: disease-dominated sites require closer disease surveillance, pest-dominated sites require stronger pest monitoring, and disease–pest complex sites require coordinated assessment of both diseases and insect pests. These recommendations are intended to guide future surveillance design and should not be interpreted as validated control thresholds, predictive rules, or direct evidence for specific control measures.

4.5. Limitations and Future Perspectives

This study has several limitations. First, the analysis was based on a single-year monitoring dataset from 2025, and the field survey was conducted once in late August, when foxtail millet was at the grain-filling stage. Therefore, the results represent a cross-sectional description of disease and pest occurrence at this specific crop developmental stage in that year. They cannot be used to infer seasonal dynamics, annual disease–pest dynamics, long-term temporal trends, or interannual variation. Multi-year and multi-stage monitoring will be necessary to determine whether the patterns observed in this study are stable across years and growth stages. Long-term monitoring is also important for understanding pest dynamics and plant disease epidemiology [37–40].

A related limitation is that harmful organisms infecting or damaging foxtail millet mainly at early developmental stages, such as emergence, seedling growth, or stem elongation, may have been missed or underestimated by the late-August survey. Consequently, the disease and pest lists reported in this study should not be interpreted as a complete inventory of all potentially harmful organisms affecting foxtail millet throughout the entire growing season. Instead, they describe the major diseases and insect pests observable during the grain-filling-stage survey. Future monitoring should include repeated assessments across key growth stages to construct a more complete seasonal profile of foxtail millet disease and pest occurrence.

At the same time, the grain-filling-stage survey has practical relevance for routine field monitoring because many common foxtail millet diseases and insect pests included in the monitoring checklist are more readily observed during the middle to late growth stages,

when field symptoms, damaged organs, and pest occurrence are usually more apparent. Disease and pest occurrence during this period may also be more directly related to yield formation and harvest-stage management decisions. Therefore, the present study provides a grain-filling-stage monitoring baseline, but it should be complemented by multi-stage surveys in future studies. Second, survey site numbers were not evenly distributed among regions. The North China–Huang-Huai region included 46 sites, whereas Northeast China and the Northwest dryland region each included 19 sites. This imbalance may influence regional comparisons. The results should therefore be interpreted as patterns within the present monitoring dataset rather than absolute estimates of regional disease–pest risk.

Third, exact geographic coordinates of individual survey sites were not available. Spatial visualization was therefore conducted at the provincial scale by aggregating site-level records within provinces. The provincial maps provide useful spatial summaries, but they do not support fine-scale spatial clustering or hotspot analysis.

Fourth, disease and pest identification in this study was based on expert field diagnosis or expert field identification using visible symptoms, affected organs, typical damage patterns, field appearance, external morphological features, and the revised monitoring checklist. This approach is suitable for routine field monitoring and regional comparison of common foxtail millet disease and pest categories. However, no pathogen isolation, molecular diagnostic confirmation, voucher specimens, detailed taxonomic examination, or specimen-based verification was performed. Therefore, the disease and pest records should not be interpreted as laboratory-confirmed pathogen records or specimen-confirmed species-level occurrence records. In particular, group-level pest records, such as aphids, mites, stink bugs, and mole crickets, should be interpreted at the monitoring-category level rather than as confirmed species-level occurrence records. Future studies should include laboratory diagnosis, molecular identification, or specimen-based taxonomic confirmation for atypical symptoms, uncertain records, or potentially new disease or pest occurrences.

Fifth, some original records were missing or recorded as categorical intervals or qualitative descriptions. Although interval midpoints and standardized values were used for quantitative analysis, these transformations inevitably introduced uncertainty and may have influenced subsequent analyses. For example, midpoint conversion can create artificial precision, simplify within-class variation, affect estimates of mean occurrence intensity, and influence the construction of relative disease and pest pressure indices. It may also affect site classification and correlation strength when converted numerical values are used in downstream analyses. In addition, the same occurrence classes were used across different diseases and pests for standardization, but these classes do not imply that all organisms have the same epidemiological characteristics, economic importance, or damage potential. Therefore, the numerical results should be interpreted as semi-quantitative indicators of regional disease–pest pressure rather than precise measurements of field incidence, infestation rate, insect abundance, or economic damage.

Sixth, disease severity data were available only for foxtail millet blast and foxtail millet rust. These severity records were not included in the main disease pressure index to avoid double weighting these two diseases and to maintain a consistent incidence-based framework across all nine monitored diseases. However, excluding severity information may reduce the epidemiological resolution of the disease pressure index, especially for diseases with large differences between low-level occurrence and severe outbreaks. In addition, disease richness and pest richness were calculated from presence–absence data. These indices are useful for describing occurrence breadth, but they assign equal weight to rare detections and severe outbreaks. As a result, richness values should be interpreted together with pressure indices and occurrence intensity, rather than as independent indicators of biological damage, economic impact, or field control priority. Seventh, the

relative pressure indices and disease–pest complex type classification constructed in this study were designed for internal comparison among sites and regions. They provide composite measures of disease–pest pressure, but they should not be interpreted as standard disease severity indices, economic injury levels, crop loss estimates, or validated control thresholds. Because validated yield-loss functions, economic damage data, and expert-derived organism-specific weights were not available for all monitored diseases and pests, equal weights were used in the composite indices. This assumption makes the indices transparent and reproducible, but it also limits their biological significance. The 0.85 and 1.15 cut-off values used to distinguish pest-dominated, disease-dominated, and relatively balanced sites were empirical tolerance thresholds. Although the sensitivity analysis using alternative thresholds showed that the main classification pattern was generally stable, the classification of a small number of borderline sites remained threshold-dependent. Future studies with multi-year datasets, yield-loss records, and independent expert validation will be needed to refine these indices and evaluate their practical relevance for field monitoring and management. Finally, the regional comparisons in this study were based on disease and pest occurrence records, but detailed environmental and agronomic variables were not included in the dataset. Factors such as temperature, rainfall, humidity, cultivar composition, sowing date, fertilization, pesticide use, cropping system, and field management practices may influence disease and pest occurrence. Because these variables were unavailable, the ecological drivers of regional differences could not be evaluated directly. Therefore, the regional comparisons should be interpreted as descriptive patterns rather than causal explanations. Future studies should integrate disease–pest monitoring data with meteorological records, cultivar information, agronomic management data, and field-level environmental variables to improve ecological interpretation and identify the drivers of regional disease–pest variation.

Despite these limitations, this study provides a multi-regional baseline for understanding disease–pest complexes in foxtail millet at the grain-filling stage. The findings highlight the value of combining occurrence spectrum analysis, regional comparison, pressure-based classification, provincial-scale visualization, and co-occurrence analysis to describe field-level disease–pest patterns. These results should be interpreted as a descriptive monitoring baseline rather than as evidence of full-season disease–pest dynamics, causal mechanisms, or validated control thresholds, and they provide a starting point for future multi-stage, multi-year, and mechanism-oriented studies of foxtail millet disease–pest occurrence.

5. Conclusions

This study analyzed a 2025 field-monitoring dataset from 84 foxtail millet survey sites across northern China. The analysis characterized the occurrence spectrum, regional variation, relative pressure, complex types, spatial patterns, and co-occurrence relationships of major diseases and insect pests observed during a single grain-filling-stage survey.

The results showed that foxtail millet diseases and insect pests occurred as complex field assemblages rather than as isolated stressors during the grain-filling-stage survey. Foxtail millet blast, millet downy mildew, and foxtail millet sheath blight were the dominant field-diagnosed disease categories. Stink bug-related records represented by the hyaline grass bug, double-spotted long-tarsed leaf beetle records, armyworm records, foxtail millet leaf beetle records, and Asian corn borer records were among the most widely recorded insect pest variables during the grain-filling-stage survey.

Disease–pest composition, richness, and relative pressure differed among regions. Northeast China showed higher disease richness and total disease–pest richness. The North China–Huang-Huai region and Northeast China showed higher total disease–pest

pressure than the Northwest dryland region. Provincial-scale maps further illustrated spatial heterogeneity in total disease–pest pressure and dominant disease–pest complex types.

Based on relative pressure indices, survey sites were classified into low-occurrence, disease-dominated, pest-dominated, and disease–pest complex types. The pest-dominated type was the most common, accounting for 47.62% of all sites. This classification provides an exploratory framework for identifying different disease–pest pressure structures and can support preliminary classification-based field monitoring. However, the classification should not be interpreted as a validated biological threshold or direct control recommendation.

Co-occurrence analysis revealed multiple strong positive associations among diseases, among insect pest variables, and between diseases and insect pest variables. These associations indicate that foxtail millet diseases and insect pests showed clear combined occurrence patterns in the 2025 grain-filling-stage monitoring dataset. However, these co-occurrence relationships should be interpreted as statistical associations rather than causal interactions, vectoring relationships, or shared epidemiological mechanisms.

Overall, this study provides a multi-regional baseline for understanding disease–pest complexes in foxtail millet during the grain-filling stage. The findings can support integrated monitoring systems, region-specific surveillance, provincial-scale risk visualization, and exploratory classification-based interpretation of foxtail millet diseases and insect pests. Because the dataset was cross-sectional and field-monitoring based, the results should not be interpreted as evidence of full-season disease–pest dynamics, causal interactions, or validated control thresholds. Future studies should incorporate multi-year monitoring data, repeated surveys across key crop growth stages, environmental variables, cultivar information, field management records, laboratory diagnostic confirmation, specimen-based pest identification, and yield-loss information to clarify the drivers of disease–pest occurrence, identify full-season disease and pest succession, and improve future disease–pest risk assessment [37–40,46,48].

Supplementary Materials: The following supporting information can be downloaded at: <https://www.mdpi.com/article/10.3390/agriculture16131465/s1>, Table S1: Transformation rules for categorical field-monitoring records; Table S2: Complete occurrence statistics of major field-diagnosed foxtail millet diseases categories in 2025; Table S3: Complete occurrence statistics of major insect pest variables in foxtail millet in 2025; Table S4: Regional composition of major field-diagnosed disease categories and insect pest variables; Table S5: Richness and relative pressure characteristics of different disease–pest complex types; Table S6: Complete list of strong positive co-occurrence pairs retained after false discovery rate correction among field-diagnosed disease categories and insect pest variables; Table S7: Pairwise Pearson correlation coefficients, raw *p*-values, and sample sizes for binary occurrence variables of field-diagnosed disease categories and insect pest variables; Table S8: GIS attribute table for provincial mapping; Table S9: Sensitivity analysis of disease–pest complex type classification under alternative tolerance ranges.

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Abbreviations

The following abbreviations are used in this manuscript:

BYDV	Barley yellow dwarf virus
FDR	False discovery rate
GIS	Geographic information system
IPM	Integrated pest management
NA	Missing value
SPSSAU	Statistical Product and Service Software Automatically

Appendix A. Disease and Insect Pest Names and Abbreviations Used in the Figures

Table A1. Full names, checklist-associated scientific names or representative labels, and abbreviated labels used in the figures.

Common Name	Scientific Name	Abbreviation Used in Figures	Category	Remarks
Foxtail millet blast	<i>Pyricularia setariae</i>	<i>P. setariae</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Foxtail millet rust	<i>Uromyces setariae-italicae</i>	<i>U. setariae-italicae</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Millet downy mildew	<i>Sclerospora graminicola</i>	<i>S. graminicola</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Foxtail millet nematode disease	<i>Aphelenchoides besseyi</i>	<i>A. besseyi</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Bacterial leaf stripe of millet	<i>Acidovorax avenae</i>	<i>A. avenae</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Foxtail millet sheath blight	<i>Rhizoctonia solani</i>	<i>R. solani</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Foxtail millet smut disease	<i>Ustilago crameri</i>	<i>U. crameri</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Foxtail millet ear rot	<i>Fusarium graminearum</i>	<i>F. graminearum</i>	Disease	Expert field-diagnosed disease category; causal agent not laboratory-confirmed in this survey
Red leaf disease	Barley yellow dwarf virus	BYDV	Disease	Expert field-diagnosed disease category; viral causal agent not laboratory-confirmed in this survey
Foxtail millet leaf beetle records	<i>Oulema tristis</i>	<i>O. tristis</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey

Table A1. Cont.

Common Name	Scientific Name	Abbreviation Used in Figures	Category	Remarks
Asian corn borer records	<i>Ostrinia furnacalis</i>	<i>O. furnacalis</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Millet stem borer records	<i>Chilo infuscatellus</i>	<i>C. infuscatellus</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Millet shoot fly records	<i>Atherigona biseta</i>	<i>A. biseta</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Armyworm records	<i>Mythimna separata</i>	<i>M. separata</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Double-spotted long-tarsed leaf beetle records	<i>Monolepta hieroglyphica</i>	<i>M. hieroglyphica</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Stink bug-related records	<i>Liorhyssus hyalinus</i>	<i>L. hyalinus</i>	Insect pest group	Group-level pest record; <i>L. hyalinus</i> was used only as a representative label in the revised monitoring checklist and figure labeling
Cotton bollworm records	<i>Helicoverpa armigera</i>	<i>H. armigera</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Spider mite-related records	<i>Tetranychus cinnabarinus</i>	<i>T. cinnabarinus</i>	Insect pest group	Group-level pest record; <i>T. cinnabarinus</i> was used only as a representative label in the revised monitoring checklist and figure labeling
Aphid-related records	<i>Rhopalosiphum maidis</i>	<i>R. maidis</i>	Insect pest group	Group-level pest record; <i>R. maidis</i> was used only as a representative label in the revised monitoring checklist and figure labeling
Rice leaf folder records	<i>Cnaphalocrocis medinalis</i>	<i>C. medinalis</i>	Insect pest	Expert field-identified pest record; not specimen-confirmed in this survey
Mole cricket-related records	<i>Grylotalpa unispina</i>	<i>G. unispina</i>	Insect pest group	Group-level pest record; <i>G. unispina</i> was used only as a representative label in the revised monitoring checklist and figure labeling

Note: Disease variables refer to expert field-diagnosed disease categories based on visible symptoms and the revised monitoring checklist. The listed causal agents are checklist-associated or commonly reported causal agents and should not be interpreted as laboratory-confirmed pathogen identification in this survey. Pest variables refer to expert field-identified pest records or pest-group records in the monitoring dataset. For group-level pest records, representative species names were used only for consistency with the revised monitoring checklist and figure labeling. These representative labels should not be interpreted as specimen-confirmed species-level occurrence records. To improve figure readability, the abbreviated labels listed in this table are used in the figures.

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