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Climate Smart Pathology: Prediction and Managing Shifts in Pathogen Dynamics Under Changing Agroecosystems

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Through variations in temperature, precipitation, severe events, and CO_2 concentration, climate change is changing the epidemiology of plant infections. This is causing changes in the life cycles, geographic ranges, host susceptibility, and vector dynamics of the pathogens. Crop yield, food security, and the sustainability of agroecosystems are all directly threatened by these changes. The current understanding of (1) how climate drivers change pathogen biology and disease expression, (2) evidence of range shifts and new host-pathogen encounters, (3) modeling approaches and predictive tools for predicting disease risk under climate scenarios, and (4) integrated, climate-smart management strategies—from breeding, agroecological practices, and policy interventions to monitoring and forecasting—is summarized in this review. In order to make plant health systems climate-smart, we identify research and implementation gaps and offer a transdisciplinary, multi-scale roadmap that includes strengthening capacity for vulnerable farming systems, developing climate-resilient cultivars, improving mechanistic models in conjunction with phenology and remote sensing, harmonizing surveillance, and adaptive integrated pest management (IPM). In order to safeguard crop health in the face of climate change, the suggestions place a strong emphasis on workable solutions that combine adaptation and mitigation.

Introduction

Climate has a direct impact on plant health and agriculture. Plant pathogens, which include bacteria, viruses, nematodes, oomycetes, fungus, and the arthropod vectors that spread them, are susceptible to changes in temperature, moisture content, CO_2, and the seasons. These sensitivity result in changes in pathogen fitness, reproduction, development rates, survival, dispersion, and interactions with natural adversaries and hosts as the environment changes. As a result, crop diseases' geographic distribution and severity are shifting, which has important ramifications for global food security and yield stability. Recent syntheses emphasize that when evaluating the climatic influence on agriculture, biotic pressures must be taken into account in addition to abiotic challenges. These concerns are framed in this review under the general heading of climate-smart pathology, which is the science and practice of anticipating, tracking, and controlling plant diseases in agroecosystems in order to preserve resilience and production in the face of climate change. We concentrate on evidence of range changes and the appearance of new diseases, pathogen response mechanisms to climatic causes, prediction and modeling tools, and management approaches that are useful to farmers and policymakers. We place a strong emphasis on practical strategies that combine breeding, agroecology, forecasting, monitoring, and governance.

How climate drivers alter pathogen biology and disease expression

Temperature, phenology and thermal niches

One of the main factors influencing the life cycle of pathogens and vectors is temperature. While the developmental rates of vectors (such as aphids and mites) increase with warming up to species-specific limitations, the rates of reproduction and infection for bacteria and fungus are governed by thermal optima. Many pests and diseases may survive the winter better in warmer climates, which can reduce mortality bottlenecks and allow for earlier seasonal breakouts. On the other hand, temperatures above thermal maxima have the ability to cause host-pathogen mismatches by suppressing some infections or forcing changes in seasonal timing (phenology). The intricacy of thermal reactions is shown by mechanistic and empirical investigations; some pathosystems exhibit nonlinear responses as a result of interacting elements (moisture, host phenology), while others augment with mild warming.

Moisture and humidity effects

Numerous foliar fungal and oomycete diseases, such as late blight, mildews, and rusts, are highly reliant on moisture: spore germination, infection, and sporulation are fueled by free water and high relative humidity. Therefore, changes in precipitation regimes, such as longer dry periods and larger rainfall events, may change the frequency and geographical patterns of outbreaks. While drought stress may in some systems enhance vulnerability (altered plant defense), even if pathogen reproduction is restricted, increased humidity in other places prolongs periods that are conducive to disease.

Elevated CO_2 and plant defense trade-offs

A slower-acting driver, elevated atmospheric CO_2, affects plant physiology (e.g., changed C:N ratios, stomatal conductance, growth rates) in ways that might impact pathogen success and host vulnerability. Depending on the pathosystem, some studies reveal higher biomass but lower tissue nitrogen, which may either halt or accelerate the development of pathogens. Furthermore, the timing of host susceptibility may be changed by CO_2-mediated phenology shifts. As a result, the overall impact of CO_2 varies depending on the situation and is best understood in conjunction with water availability and temperature.

Vector dynamics and disease transmission

Both vector biology and pathogen replication inside vectors are impacted by climate, making vector-borne diseases doubly susceptible. Warming has the potential to decrease generation periods, change seasonal windows for transmission, boost vector population growth, and extend vector ranges poleward and to higher altitudes. These impacts have been connected to the spread of bacterial and viral illnesses that are mediated by insect vectors, such as psyllids, aphids, and whiteflies.

Evidence for range shifts, emergence, and changing disease burden

Observed range expansions and new outbreaks

The establishment of illnesses in previously inappropriate places and the poleward or elevational migrations of infections and vectors are documented in an increasing number of empirical case studies. Rusts and other fungal diseases, for instance, have shown non-linear range dynamics, with local intensifications in some regions and contractions in others. These dynamics are often influenced by intricate relationships between host distribution, climate, and land use. These observed changes serve as an early warning that a number of viruses may come into contact with new hosts and agroecosystems, which might have unanticipated epidemiological consequences.

Novel host–pathogen encounters and invasions

When naïve hosts lack resistance, range changes raise the possibility of new host–pathogen interactions, which may lead to serious outbreaks. Invasive danger is increased by global commerce, plant material migration, and changing climate appropriateness. By highlighting hotspots where commerce, crop presence, and climatic suitability intersect, modeling and monitoring can identify areas that are more vulnerable to new introductions.

Impacts on food security and ecosystems

The combined influence of abiotic stressors and disease alterations brought on by climate change affects yield stability. According to reviews and meta-analyses, crop losses due to biotic stressors may rise in the future unless management changes. Smallholder systems in tropical and subtropical regions are especially vulnerable, since their ability to adapt is restricted. Pathogen alterations endanger natural plant communities and ecosystem services (pollination, carbon storage), which have an impact on agricultural landscapes in addition to crop output.

Modeling techniques and predictive tools

Prediction is essential to effective climate-smart pathology because it allows treatments to be focused by anticipating where and when risk will shift. There is a toolkit of complimentary modeling techniques, each with advantages and disadvantages.

Correlative species distribution models (SDMs) forecast possible habitat suitability under scenarios by combining climatic factors with observed occurrence records (e.g., MaxEnt, BIOCLIM). They are helpful for pathogens/vectors with well-documented incidence and for mapping risks on a large scale. Sensitivity to sample bias, transferability in unfamiliar climates, and the incapacity to record microclimatic refugia or biological interactions are some of the limitations. Robustness may be enhanced by ensembles and meticulous assessment (e.g., MESS/novel climate testing).

Mechanistic (process-based) models

Life-cycle activities, such as spore generation, infection likelihood, and latent periods, are simulated using mechanistic models as functions of environmental causes. These models are better able to represent transient dynamics, nonlinear responses, and management impacts (e.g., cultivar phenology, fungicide scheduling). They are effective for scenario testing and intervention planning, but they need thorough parameterization and validation. The integration of mechanistic models with actual phenology and microclimate data has been emphasized in recent calls.

Models of epidemiology and metapopulation

Epidemiological models (SIR/SEIR frameworks) and metapopulation techniques enable assessment of spread over diverse host environments at landscape sizes, taking into consideration dispersion, local extinction/recolonization, and management strategies. These may be combined with weather and connectivity data to create dynamic risk maps that are helpful for quarantine decisions and regional planning.

Forecasting that is both hybrid and data-driven

Operational forecasting systems are produced by combining mechanistic and correlative methods with data assimilation (e.g., integrating field surveillance, remote sensing, and near-real-time weather). While mechanical structure offers interpretability and transferability under changing circumstances, machine learning techniques may identify patterns in complicated datasets and enhance short-term projections. Regional operational examples are starting to appear, but they need consistent data feeds.

Monitoring and early warning — the foundation of climate-smart pathology

Integrated monitoring improves lead time for interventions and supports adaptive management. Investment in digital tools and training is particularly cost-effective in regions with high disease risk and limited formal surveillance. Prediction is only as useful as the monitoring that supports it. Climate-smart plant health systems need harmonized, multi-scale surveillance:

- **Field surveillance**: farmer reporting networks, sentinel plots, and extension services to detect early outbreaks.
- **Remote sensing and phenology**: satellite and drone imagery can detect crop stress, canopy conditions, and disease signatures at scale.
- **Pathogen diagnostics**: rapid molecular assays (LAMP, qPCR), eDNA, and portable sequencing for early confirmation.

- **Data platforms**: interoperable data pipelines linking weather, surveillance, crop distribution, and management records to feed models and advisories.

Climate-smart disease management strategies

Climate-smart pathology requires reshaping both technical and institutional responses. Below are complementary strategies organized by scale and mechanism.

1. Biosecurity and prevention

Reduced introductions and slowed dissemination are achieved by risk-based movement restrictions, phytosanitary inspections, and strengthened quarantines. Inspection priorities are aided by risk mapping that makes use of SDMs and trade data. The most economical approach to new intrusions is still early detection combined with quick action (eradication or containment).

2. Breeding and deploying host resistance that is climate resilient

The key is long-lasting resistance. Breeding programs must use expedited breeding (speed breeding, genomic selection), genomic prediction for several stress complexes (abiotic + biotic), and different resistance genes to anticipate changing disease pressures. In conditions that fluctuate, breeding for tolerance and partial resistance may be more resilient. Additionally, variety combinations and crop diversification lessen the severity of epidemics.

3. Adaptive integrated pest management (IPM)

Classical IPM — combining cultural, biological, and chemical measures — must be reframed for dynamic risk. Key elements include:

- Climate-informed timing of interventions (using forecasts to optimize fungicide or biocontrol application windows).
- Cultural practices to reduce inoculum (crop residue management, rotation, adjusted planting dates).
- Biological control and conservation of natural enemies tailored to changing phenologies.
- Rationalized pesticide use to limit resistance development and preserve ecosystem services. Mechanistic models can optimize timing and reduce unnecessary sprays.

4. Agroecological and landscape methods

Regional inoculum pressure is decreased by managing disease at landscape sizes (buffer strips, natural enemy habitat, and planned planting dates). Cover crops, organic amendments, and varied rotations are examples of agroecological techniques that enhance soil health and plant vigor and may increase resistance to biotic and abiotic stresses. By restricting monoculture hotspots, these measures may also lessen susceptibility to incursions.

5. Advisory and decision support services

Farmers get customized advice from operational decision support systems (DSS) that include local agronomy, disease models, and weather predictions. Participatory extension, SMS warnings, and mobile applications help close the gap between farmers and researchers. DSS co-design with stakeholders guarantees adoption and usefulness.

6. Institutions, money, and policy

Policies must support breeding and surveillance, encourage private-public collaborations for forecasting and diagnostics, finance fast reaction capabilities, and subsidize risk-reducing measures. Since investments in plant health safeguard production and offer significant returns, climate financing methods should include plant health as a component of adaptation portfolios.

Research gaps and implementation issues

Scaling problems and data limits

Inadequate integration of farm management variables, restricted microclimate observations, and scarce disease incidence data hinder many prediction models. It is crucial to increase both the volume and quality of data via crowdsourcing, standardized monitoring procedures, and easily available diagnostic tools.

Complexity of interactions between many drivers

Because of the interplay between temperature, moisture, CO_2, host genetics, and biotic ecosystems, pathogen responses are often context-dependent. Hybrid modeling that incorporates mechanistic insight is a goal since simple correlative predictions run the risk of mispredicting under unique climates. Models will be enhanced by experimental studies to measure parameter values across environmental gradients (thermal performance curves, moisture response curves, vector competence in diverse climates).

Institutional and socioeconomic obstacles

Market structures, knowledge, input accessibility, and incentives all play a role in the adoption of climate-smart activities. Smallholders in low-income areas may not have the resources to obtain resistant seed or act on projections. To provide fair solutions and funding sources, social science research is necessary.

Anticipating evolutionary responses

Both environment and management-imposed selection pressures may cause pathogens and vectors to quickly develop (e.g., virulence alterations, fungicide resistance). Long-term hazards may be decreased by keeping an eye on the genetic makeup of the pathogen population and taking evolutionary potential into account when designing management strategies (e.g., integrated chemical rotations, mosaic deployment of resistance).

A roadmap for climate-smart pathology (practical steps)

1. Streamline monitoring by investing in portable diagnostics, growing sentinel networks, standardizing reporting, and using genomic surveillance for early detection.
2. Create hybrid modeling platforms: create short-term predictions and long-term scenario maps by combining mechanistic disease models with SDMs and data assimilation pipelines (weather, remote sensing, field reports). Check against previous outbreaks.
3. Defensively prioritize breeding goals by investing in multi-trait breeding (disease resistance + abiotic resilience), ranking hazards regionally using climate forecasts, and accelerating variety release pipelines to adapt to changing pressures.
4. Operationalize DSS and advisory services: collaborate to create farmer-centered decision-making tools that connect to extension services and convert predictions into concrete actions (such as rescheduling spraying or planting dates).
5. Landscape coordination: use incentives and legislative assistance to promote cooperative disease control among farms (synchronized practices, regional monitoring).
6. Integrate plant pathology into national CSA policies and adaptation funds to provide ongoing support for breeding and monitoring. This will help mainstream plant health in CSA and climate finance.

Conclusion

Climate-smart pathology, which is prediction-led, surveillance-driven, mechanistically informed, and socially integrated, reframes plant disease management for a changing climate. Agriculture may lower disease risk and safeguard production in the face of changing circumstances by combining enhanced surveillance, hybrid predictive models, climate-resilient breeding, adaptive IPM, and landscape-scale coordination. Data investments, farmer and extension capacity development, legislative incentives, and interdisciplinary research that combines ecology, epidemiology, climatology, genetics, and social sciences are all need to achieve this. The potential benefits of robust crops, lower losses, and more secure food systems in a warming future outweigh the urgency.

References

1. Angelotti, F., et al. (2024). *A Comprehensive Review of Climate Change and Plant Diseases*. *Plants*, 13(17), 2447. https://doi.org/10.3390/plants13172447. MDPI
2. Annual Review of Phytopathology. (2022). *Climate change and plant disease review* (Vol. 58). Annual Reviews. Annual Reviews

3. Dudney, J., et al. (2021). Nonlinear shifts in infectious rust disease due to climate change. *Nature Communications*, 12, Article 1. https://doi.org/10.1038/s41467-021-25182-6. Nature
4. Elghoul, O. (2025). *Implications for agricultural sustainability: predicting the distribution of plant pathogens under climate change*. *Frontiers in Plant Science*. (Early 2025 article). Frontiers
5. FAO. (2019). *Climate-Smart Agriculture and the Sustainable Development Goals: Mapping interlinkages, synergies and trade-offs*. Food and Agriculture Organization of the United Nations. Open Knowledge FAO+1
6. Godefroid, M., et al. (2023). Species distribution models predicting climate suitability for insect vectors. *Ecological Modelling*. ScienceDirect
7. Jiranek, J., et al. (2023). Mechanistic models to meet the challenge of climate-driven plant disease dynamics. *Philosophical Transactions B / Relevant Journal*, 2023. PMC
8. Lahlali, R., et al. (2024). Effects of climate change on plant pathogens and host interactions. *Journal of Plant Pathology* (2024 review). ScienceDirect
9. Singh, B. K., et al. (2023). Climate change impacts on plant pathogens, food security and paths forward. *Philosophical Transactions / Open Access Review*. (2023). PMC 10153038. PMC
10. Velásquez, A. C., et al. (2018). Plant and pathogen warfare under changing climate. *Trends in Plant Science*, 23(6), 540–553. https://doi.org/10.1016/j.tplants.2018.02.002. PMC
11. Yang, L. N., et al. (2023). Modeling plant diseases under climate change: advances and prospects. *Global Change Biology / Reviews*, 2023. ScienceDirect